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METHYL METHACRYLATE POLYMER CONCRETE FOR BOMB DAMAGE REPAIR: PHASE I

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METHYL METHACRYLATE POLYMER-CONCRETE

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Methyl methacrylate (MMA) polymer concrete appears to be a material which can be successfully used to rapidly repair bomb damaged runways. A research program is underway to develop monomer formulations, determine engineering design properties, develop repair procedures, conduct field tests, conduct analytical studies, and develop an implementation manual. Research in Phase I has emphasized materials characterization, development of preliminary repair procedures, and analytical and experimental behavior of repairs.

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Materials characterization studies have determined monomer formulations and polymer-concrete mechanical properties for a wide range of ambient temperatures. Possible solutions for reducing adverse effects on strength of polymer-concrete made with wet aggregate have been studied. The effect of MMA on bond to asphalt has been determined. The effect of aggregate size on mechanical properties has been investigated.

Preliminary repair concepts include the use of (1) a polymer concrete cap; (2) precast concrete slab bonded together with polymer concrete; and (3) precast concrete slabs bonded together with and overlaid with polymer concrete. Both user formulated and commercially available polymer concrete can be used.

Experimental tests have been performed on small concrete slabs repaired with polymer concrete to determine the fatigue loading characteristics. Small beams have been subjected to cyclic loading to develop the relationship between percentage of ultimate load and number of loading cycles.

Analytical studies have been performed to determine the stresses at various locations within the repair. Nomographs have been prepared which give the required depth of repair for various parameters.

PREFACE

This report was prepared by The University of Texas at Austin, Austin, Texas 78712 under Contract No. F08635-79-C-0103 with the Air Force Engineering and Services Center, Tyndall Air Force Base, Florida 32403. This work was begun in March 1979 and was completed in May 1980.

This report discusses methyl methacrylate polymer concrete materials characterization, development of preliminary bomb damage repair procedures, and analytical and experimental behavior of repairs. Characterization studies were made to determine monomer formulations and mechanical properties for different ambient temperatures and to investigate effects of wet aggregate. Preliminary repair concepts included polymer concrete caps and precast concrete slabs bonded together with polymer concrete. Studies were performed on small concrete slabs repaired with polymer concrete to determine fatigue loading characteristics, and analytical studies were accomplished to predict stresses at locations within repairs. The report does not constitute an indorsement of products discussed nor can it be used to advertise the products.

This report has been reviewed by the Public Affairs (PA) Office and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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SECTION I

INTRODUCTION

1.0 Background

The rapid repair of bomb damaged runways is of vital concern to the Air Force. Airfield pavements must be repaired rapidly so that aircraft can be launched. Current repair procedure, specified in Air Force Regulation (AFR) 93-2 (Reference 1), is based upon North Atlantic Treaty Organization (NATO) damage criteria, which require repairing three 750-pound (lb) bomb craters in four hours. The repair procedures in AFR 93-2 include backfilling the crater with debris within one foot of the surface, removing upheaved concrete, filling the top of the crater with select fill, and placing and anchoring AM-2 matting over the surface of the backfilled crater.

New developments in weapons technology have altered the repair criteria. The present threat includes many smaller weapons. As a result, instead of only a few large craters as envisioned in AFR 93-2, the repair procedures must also be able to accommodate many small and medium-sized craters.

The Air Force Engineering and Services Center (AFESC) is currently engaged in a research and development program to improve the rapid runway repair (RRR) capability. New materials and techniques are being investigated by the Engineering and Services Laboratory at Tyndall Air Force Base (AFB). This contract has the objective of developing rapid repair techniques using methyl methacrylate (MMA) polymer concrete (PC), which has been successfully used for repairs of highway structures (References 2 and 3).

1.1 Scope of Research

Phase I, which extends from 1 March 1979 to 30 April 1980, includes the following tasks:

Task 1: Materials Characterization

Task 2: Development of Preliminary Repair Concepts

Task 3: Analytical and Experimental Behavior of MMA Polymer Concrete

Phase II, which extends 1 May 1980 to 28 February 1981, includes the following tasks:

Task 4: Analytical and Experimental Behavior of MMA Polymer Concrete

Task 5: Finalization of Repair Procedures

Task 6: Field Testing of Repairs

Task 7: Development of Implementation Manual

This report summarizes the research performed in Phase I.

1.2 Nomenclature and Definitions

Synthetic polymers constitute a broad class of materials which includes polyesters, nylons, and epoxies which have been chemically transformed into high molecular weight chemical structures from simpler units called monomers. Several types of chemical reactions can be used to cause polymerization of monomers into polymers. Each class requires carefully selected formulations of monomers, additives, and reaction conditions to achieve the desired result. A number of these polymer systems have been successfully employed as substitutes for portland cement for binding aggregates together to produce polymer concrete. Acrylic polymers formed primarily from methyl methacrylate offer distinct advantages for polymer concrete systems for rapid repair of bomb damaged runways.

This application of polymer concrete places stringent requirements on both the process of polymerization and the properties of the resulting polymer. In addition, the interaction of the polymer with the selected aggregate system to form a good bond is another important requirement which can be adversely affected by extraneous matter, such as water. The most important process requirement is the rate of polymerization or the time for curing the monomer into a solid polymer. The resulting polymer must develop adequate mechanical properties to meet the requirements for the composite polymer concrete. The main mechanical property of the polymer which is of interest is the ultimate strength, which is defined as the maximum stress which the material will sustain. For polymers, this characteristic is conventionally measured in tension because most polymer failures occur in this mode rather than in compression. For many purposes, ductility of the polymer is also a critical issue in its applications. For this work, measures of polymer ductility are primarily based on the magnitude of deformation at failure in tension tests. Many of the above mentioned characteristics are indigenous to the selection of methyl methacrylate as the base monomer; however, each characteristic can be significantly affected by the formulation employed in the formation of the polymer.

Table 1 shows a general formulation for methyl methacrylate-based polymers used in polymer concrete applications. This table and the remainder of this report makes extensive use of simple abbreviations of the chemical names of the various ingredients in the formulation for simplicity and brevity. Table 2 identifies these abbreviations with the standard chemical names. The polymerization of methyl methacrylate proceeds by a free radical process, which requires a source of free radicals. This may be accomplished by a number of methods; however, the most useful for these purposes is the addition of a chemical initiator. Several types of initiators are known and employed, but peroxides are the most useful for polymer concrete applications since their decomposition into free radicals can be catalyzed (accelerated or promoted) by the addition of another suitable chemical. Thus, the initiator system is comprised of a peroxide and a promoter, whose type and proportion have dramatic effects on the rate of polymerization or curing and the resulting properties of the polymer. This work has employed benzoyl peroxide and dimethyl para toluidine, respectively, for this purpose. Other choices could have been made or will

TABLE 1. MONOMER FORMULATIONS

Basic Monomer		Initiator System	
MMA		Peroxide	Promoter
		BP	DMPT

Comonomers		Cross-Linking Agents
BA	AA	TMPTMA
EHMA	HPMA	TTEGDA
IDMA	MAA	

Plasticizers
DOP

TABLE 2. LIST OF ABBREVIATIONS

Monomers	
MMA	Methyl Methacrylate
BA	Butyl Acrylate
EHMA	2-Ethylhexyl Methacrylate
IDMA	Isodecyl Methacrylate
AA	Acrylic Acid
MAA	Methacrylic Acid
HPMA	Hydroxypropyl Methacrylate
Initiator Agents	
BP (also BPO or BzP)	Benzoyl Peroxide
DMPT (also DMT)	Dimethyl Para Toulidine
DMA	Dimethyl Aniline
Cross-Linking Agents	
TMPTMA	Trimethylolpropane Trimethacrylate
TTEGDA	Tetraethylene Glycol Diacrylate
Plasticizers	
DOP	Dioctyl Phthalate
TCP	Tricresyl Phosphate

be made in subsequent work on this project if needed; however, this sytem has proved sufficiently versatile and effective. Polymer technology frequently makes use of mixtures of monomers to form copolymers since this provides an effective means of tailoring the polymerization process and the polymer to meet specific needs. In this report, a second monomer when added to methyl methacrylate is referred to as comonomer and would include, but not be limited to, butyl acrylate or any of the others mentioned in Table 1. These comonomers have been screened for their effectiveness in improving polymerization rate, polymer ductility, or adhesion of polymer to set aggregate. The polymers mentioned thus far are linear in their molecular structure and may be likened to a train (a polymer chain) formed from box cars, flat cars, etc. (monomers and comonomers). Chemical monomers which possess multiple functionality can be added to introduce branching and subsequently cross-linking between polymer chains. These materials are known as cross-linking agents, and the most typical one employed in polymer concrete formulations is trimethylolpropane trimethacrylate. These materials dramatically alter the polymerization rate and polymer properties. Sometimes non-reactive plasticizers are incorporated into polymer formulations to add ducility to the resulting material. Plasticizers are used in prepackaged polymer concrete formulations but have not been employed in the cast-in-place formulations used here. A variety of other chemical ingredients may be added to the formulation as needed to alter workability or behavior.

These materials and concepts form an arsenal of tools for problem solving which can be employed in any polymer concrete application, and a significant amount of this research has been devoted to finding and optimizing formulations for the various environmental conditions of repair of bomb damaged runways. Subsection 2.1 illustrates typical results that have been generated in the process of defining these formulations. These results and others will be employed in Phase II for solving specific problems that arise. If solutions cannot be found within these results, other combinations based on prior experience will be sought.

SECTION II

MATERIALS CHARACTERIZATION

2.0 Introduction

Task 1 had the objective of developing polymer concrete formulations that would satisfy the criteria established by the Air Force for bomb damage repair. The primary considerations were to develop (1) monomer formulations that would set in one hour or less at temperatures in the range of $-25^{\circ}F$ to $125^{\circ}F$; (2) develop monomer formulations that would bond to asphalt and cure in one hour or less; (3) determine effects of aggregate types, gradations, moisture content, and temperatures; (4) determine relationship between moisture content of aggregate and strength of the polymer concrete and develop procedures or monomer formulations to permit the use of wet aggregate; and (5) determine flexural strength, modulus of elasticity, and fatigue strength of polymer concrete.

Two types of MMA-based polymer concrete systems were investigated: contractor-formulated systems and commercially-available systems. Several monomer systems were studied for the contractor-formulated polymer concrete.

2.1 Polymerization Process and Polymer Properties

2.1.1 Polymerization Process. The main aspects of the polymerization process of interest are the rate of cure and, to a lesser extent, the degree to which the monomer has been converted into polymer (conversion). These issues are greatly affected by temperature, type and amount of initiator agents, type and amount of comonomer, and type and amount of cross-linking agents employed in the formulations.

Figure 1 illustrates the effect of some of these variables on the rate of curing. Detailed monitoring of polymerization rate involves complex techniques, but an adequate measure for present purposes involves measurement of the temperature of the reacting system. Polymerization is an exothermic chemical reaction, i.e., heat is evolved, and it has been found that the reaction is nearly finished. Thus, the time to peak exotherm has been used in this work as a measure of the time required for polymerization. This measurement is made by simply imbedding a thermocouple in the specimen and observing the time required for temperature to reach its maximum value. Like all chemical reactions, the rate of polymerization decreases as the temperature is lowered. This effect is shown for three different formulations in Figure 1. The reduction in rate of polymerization corresponds to an increase in the time to peak exotherm or cure time. Each formulation has a characteristic relationship between cure time and temperature. However, this relationship is greatly affected by the ingredients and their proportion in the formulation, as illustrated in Figure 1. Generally, the rate of polymerization at a given temperature

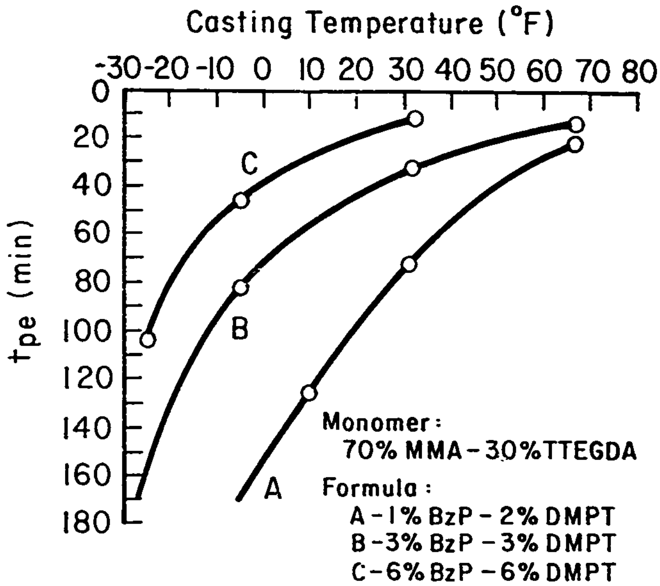


Fig. 1. Variation of Set Time with Casting Temperature

is increased by the addition of larger amounts of either initiator (benzoyl peroxide) or promoter (dimethyl para toluidine). However, the proportion of these two ingredients cannot be varied independently. Rather, experience has shown that best results in terms of cure time and polymer properties are achieved when a certain ratio, which depends on temperature, is maintained between these two ingredients.

It is of interest to note that the formulation employed in Figure 1 contains 70 percent MMA and 30 percent of a cross-linking agent, TTEGDA. Most work on polymer concrete has employed the cross-linking agent TMPTMA; however, in this research it has been discovered that the cross-linking agent TTEGDA possesses several advantages over TMPTMA. One of these is illustrated in Figure 2, where the percentage conversion of monomer to polymer is shown as a function of the type and amount of cross-linking agent. Figure 2(a) shows that addition of TMPTMA actually decreases the conversion of monomer to polymer, whereas Figure 2(b) shows that similar addition of TTEGDA does not cause such a reduction but, in fact, causes a slight increase in conversion. The primary importance of this observation has to do with the manner in which TTEGDA affects the polymerization rate as compared to TMPTMA. Figure 3 illustrates the dramatic effect that the addition of TTEGDA has on the cure time and MMA formulations. It may be observed that the addition of a substantial amount of TTEGDA serves to dramatically reduce

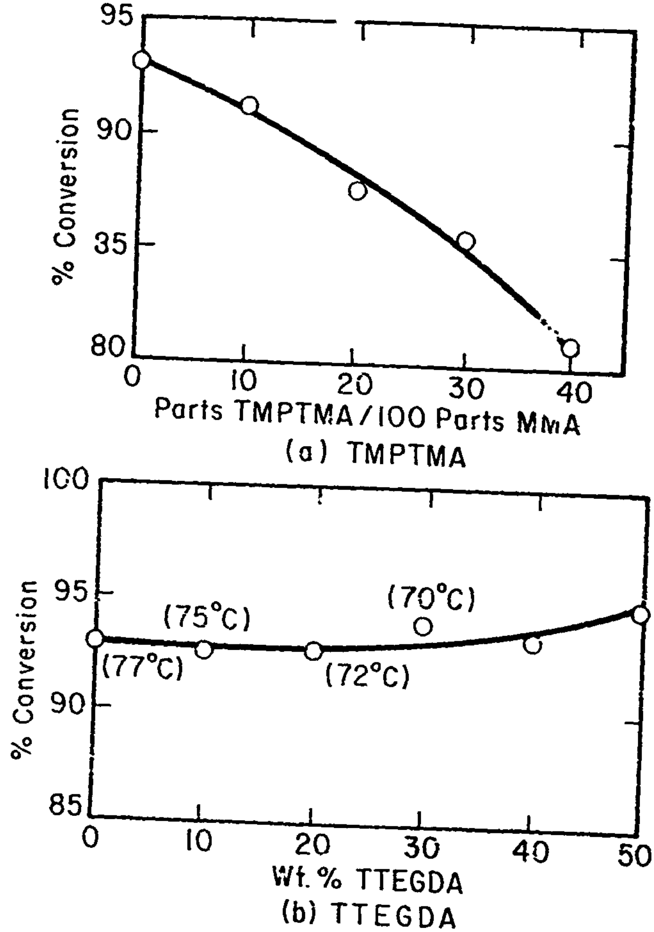


Fig. 2. Effect of Percent of TMPTMA and TTEGDA on Conversion of Monomer to Polymer

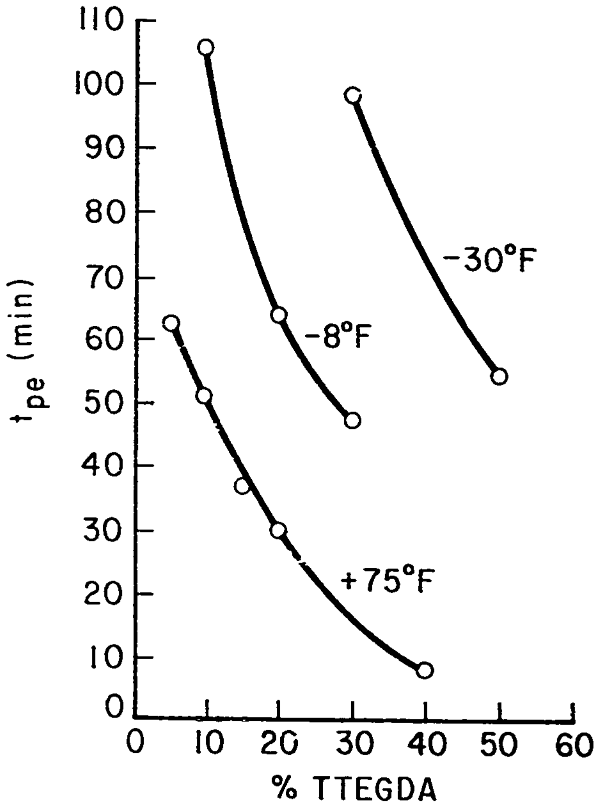


Fig. 3. Influence of TTEGDA

the length of time required to convert monomer into polymer. This is of particular importance in achieving low temperature cures within the time limits specified for bomb damage repair.

2.1.2 Polymer Properties. The properties of the polymer formed are an inherent function of the monomer formulation employed and are indirectly affected by all factors that influence polymerization rate. Polymer properties have been monitored in this project by casting dog-bone-shaped polymer specimens (without aggregate) in an aluminum mold and subsequently testing them in tension in an Instron testing machine. Figure 4 illustrates the shape of the mold cavities employed for forming polymer specimens for this purpose.

These results are typical of those generated in the laboratories which have guided the selection of monomer formulations for this work. Figure 5 shows the effect of adding the crosslinking agent TMPTMA to the mechanical properties of methyl methacrylate-based polymers. It may be observed that this ingredient has virtually no effect on the tensile modulus of the polymer. However, its addition does adversely affect the polymer, causing failure to occur at reduced levels of stress and deformation. Although addition of TMPTMA may be desirable in certain formulations to meet specific objectives, it is clear that mechanical properties are sacrificed when it is done. In many situations, polymer brittleness is a problem and formulation corrections to impart a measure of ductility are

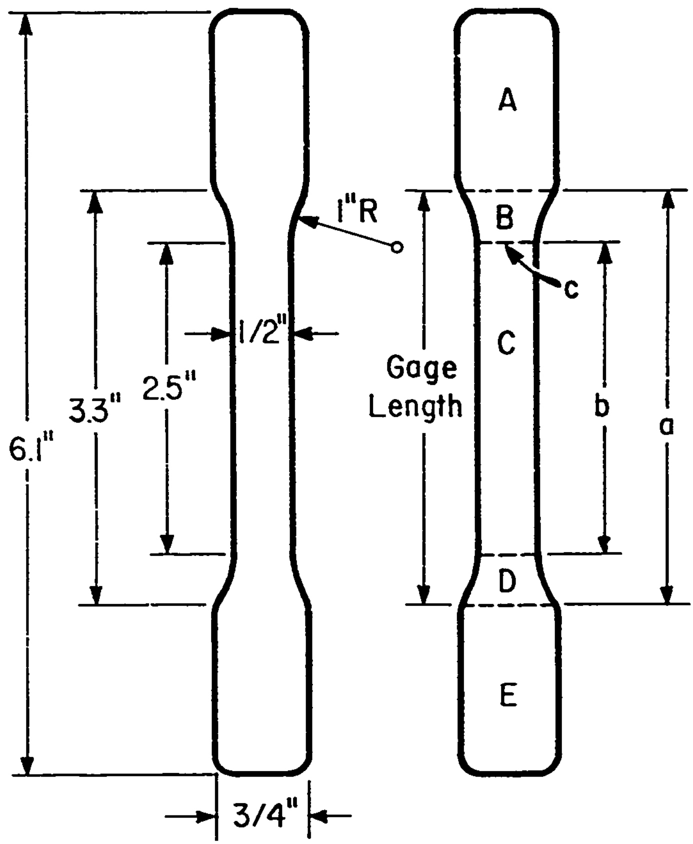


Fig. 4. Size of Dog-Bone Shaped Specimen for Tensile Testing of Polymers

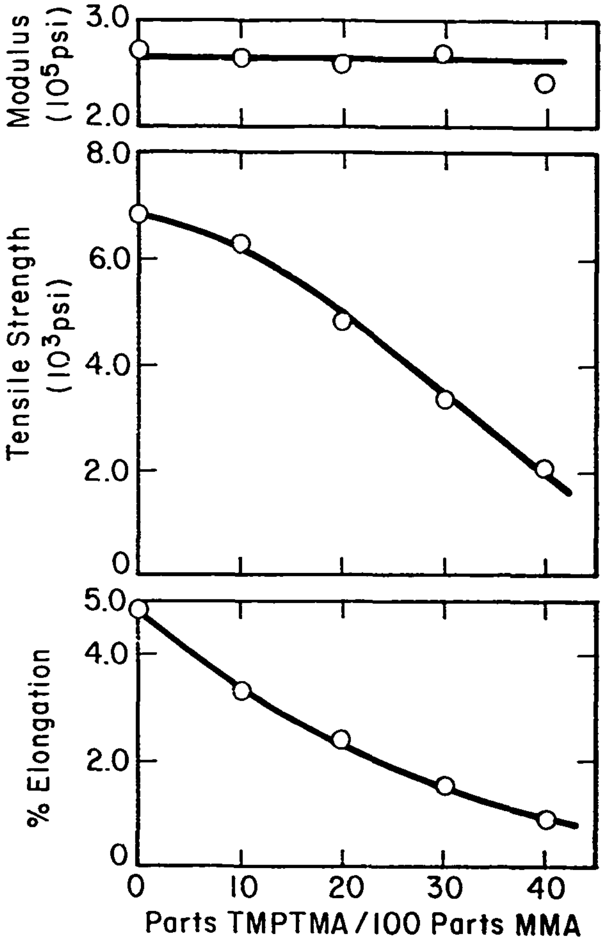


Fig. 5. Effect of TMPTMA on Mechanical Properties

required. A common approach to this situation is to add butyl acrylate to the formulation. As seen in Figure 6, this results in a dramatic improvement in the strain at failure for the polymer; however, Figure 7 shows the corresponding characteristic loss in stiffness that accompanies large additions of butyl acrylate to the formulation. While butyl acrylate is an effective comonomer for improving ductility, it has certain disadvantages, including a very obnoxious and persistent odor. Therefore, this work has been concerned with finding certain suitable replacements which do not have these objectionable characteristics. Several replacement monomers suggested by chemical manufacturers have been screened, and one typical example is 2-ethyl hexyl methacrylate. Figure 8 shows the effect this comonomer has on polymer mechanical properties. This comonomer causes slight losses in stiffness and strength with no corresponding increases in ductility, and, as a result, it has been discarded with many other candidates.

One of the surprising results obtained in this study has been the increased ductility which addition of the cross-linking agent TTEGDA provides the polymer in contrast to the loss of ductility shown in Figure 5 for TMPTMA. Figure 9 illustrates this increase in ductility caused by TTEGDA under various polymerization conditions. The beneficial effects of this material on curing rate and polymer properties have resulted in its prominent utilization in the formulations recommended here for bomb damage repair.

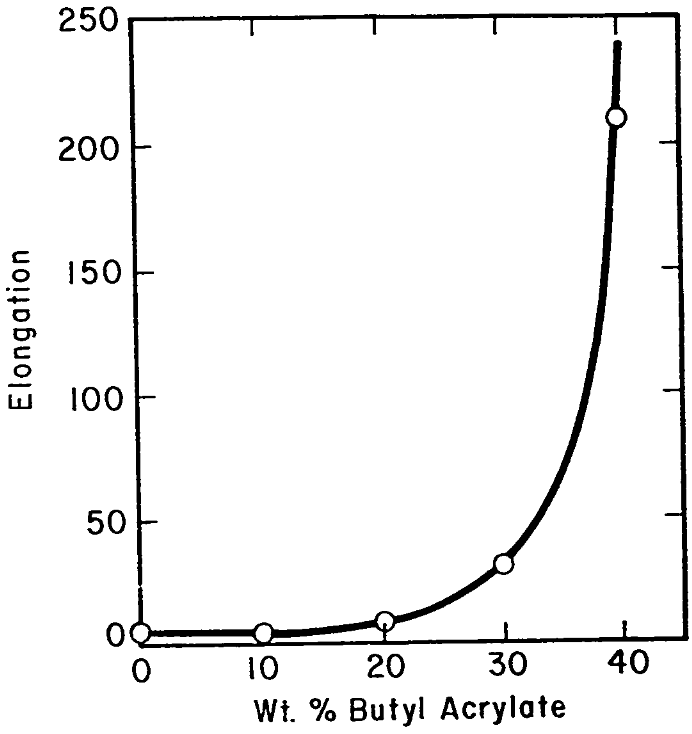


Fig. 6. Effect of Butyl Acrylate on Polymer Ductility

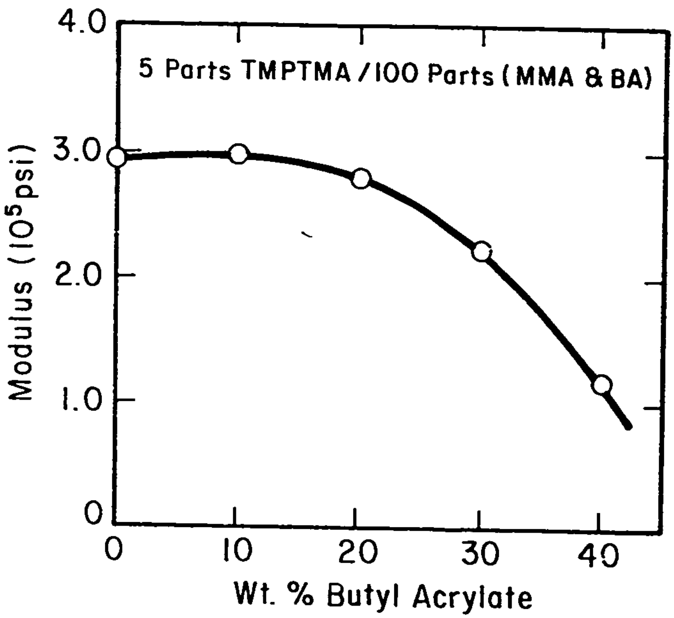


Fig. 7. Effect of Butyl Acrylate/Polymer Modulus

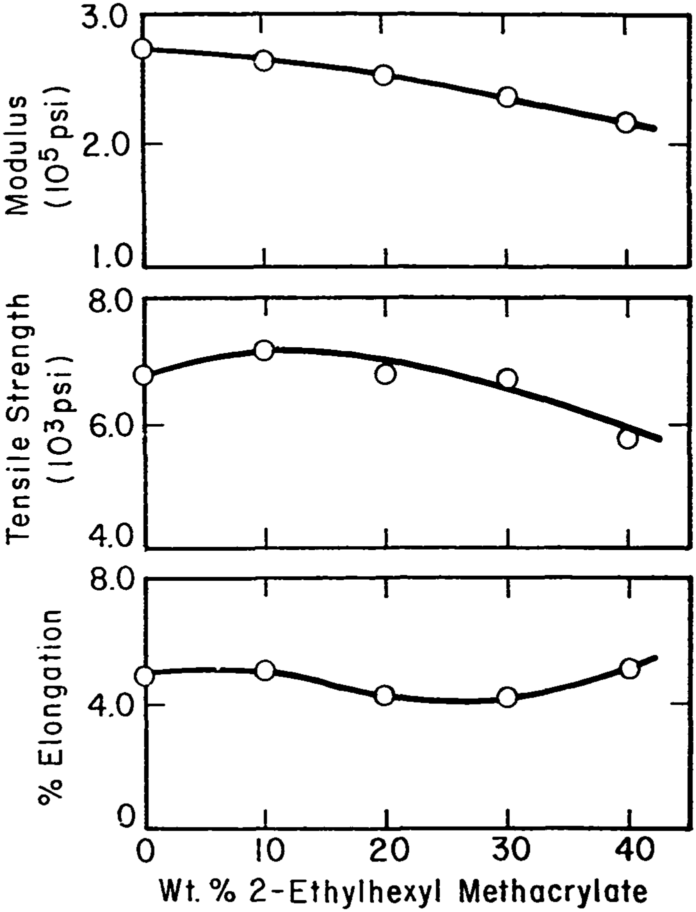


Fig. 8. Polymer Mechanical Properties

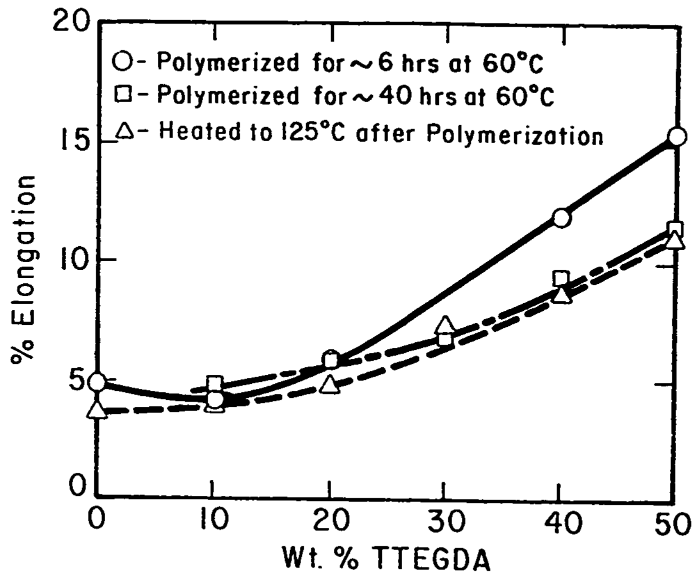


Fig. 9. Effect of TTEGDA on Polymer Ductility

2.2 MMA/TMPTMA Monomer Systems

Monomer systems using MMA/TMPTMA as the primary monomers have been widely used for polymer concrete for several years. They have been proven to produce good quality PC at normal temperatures.

2.2.1 Effect of Casting Temperature. Monomer formulations were first optimized at different temperatures (30°, 50°, 70°, and 100°F). Different percentages of BzP and DMPT were used in 10 cubic centimeters (cc) of the monomer to produce polymer; no aggregate was used in this part of the study. Table 3 indicates the results for monomer polymerized at an ambient temperature of 100°F. The initial monomer temperature was the same as the ambient temperature. The legend in Table 3 indicates the quality of the polymer, polymerization time in minutes, and peak exotherm. It should be noted that the high exotherms were obtained only when no aggregate was used. Later tests with aggregate did not produce exotherms as high as 200°F.

The results of these tests were used to select BzP to DMPT ratios for the next part of the study, which involved making 2-inch x 2-inch x 12-inch PC beams to be tested in flexure by third-point loading with a 9-inch span. Beams were cast at 30°, 70°, and 100°F. Aggregate consisted of 55 percent 3/8-inch pea gravel and 45 percent sand. The sand was a 50:50 (wt) mixture of No. 2 and No. 3 blasting sand.

TABLE 3. POLYMERIZATION OF 95% MMA/5% TMPTMA AT 100°F (38°C)

Sample Size: 10 cc

% DMPT \ %BzP	0.125	0.25	0.5	0.75	1
0.125	a	56 I 240°F	a	32 I 308°F	25 I 332°F
0.25	a	a	a	25 G 263°F	20 F 318°F
0.375	a	a	a	18 G 275°F	a
0.5	46 I 134°F	38 I 178°F	25 B 229°F	20 F 217°F	15 G 292°F
1.0	32 I 123°F	25 I 141°F	22 B 193°F	19 F 240°F	10 F 274°F

[a]Tests not performed for these combinations of BzP and DMPT

Legend:

Y	X
Z	

X - Qualitative description:
- G - Good
- F - Fair
- B - Bad
- I - Incomplete polymerization

Y - Polymerization Time (minutes)

Z - Peak Exotherm (°F)

Table A-1 in Appendix A gives the gradation of the sand. The relative proportions of BzP and DMPT were kept constant for each casting temperature. Three specimens were cast for each monomer system. The flexural strengths are shown in Tables 4, 5, and 6 for the three casting temperatures. Work time shown in the table was the time after mixing at which a 150 cubic centimeter volume of the monomer system could no longer be poured. The specimens were tested 24 hours after casting.

The casting temperature did not cause a significant difference in flexural strength, f_r (which is the same as modulus of rupture, R , for the modulus of rupture for the ASTM test). The average f_r for each formulation used was greater than 2000 pounds per square inch (psi). Figure 10 gives the BzP and DMPT levels which yielded the highest f_r for each casting temperature. Figure 11 gives the setting time of the PC which corresponded to the highest f_r as a function of casting temperature.

The effect of casting temperature on compressive strength and modulus of elasticity was obtained by tests on 3-inch x 6-inch cylinders cast at 100°, 70°, and 30°F. The monomer system was 95 percent MMA and 5 percent TMPTMA with the promoter and initiator levels obtained from Figure 10. The aggregate was the same as given in Table A-1. After casting, the specimens were left in the environmental chamber for 10 hours and then maintained at room temperature for 14 hours, during which time they were cut with a diamond-tipped saw to provide

TABLE 4. MODULUS OF RUPTURE OF PC CAST AT 100°F (38°C)[a]

% BzP	% DMPT	Work Time (min)	Set Time (min)	Peak Exotherm (°F)	f_r (psi)	Average f_r (psi)
			58	130	2104	
0.6	0.2	b	58	131	2138	2201
			58	132	2363	
			41	145	2385	
0.75	0.25	24	41	148	2205	2186
			40	150	1969	
			38	139	1924	
0.9	0.3	19	38	140	2250	2153
			38	145	2284	
			30	141	2194	
1.05	0.35	12	30	144	2368	2357
			29	151	2509	

[b]was still pourable when the peak exotherm occurred in the PC

[a]NOTES:

Monomer: 95% MMA + 5% TMPTMA
Specimen Size: 2-inch x 2-inch x 12-inch (51-mm x 51-mm x 305-mm) beam
Temperature of Specimen when mechanically tested: 70°F (21°C)
PC density: 136.6 pcf (2188 kg/m^3)
Monomer loading: 26.2% by vol; 11.5% by wt.
PC age when tested: 24 hr.

TABLE 5. MODULUS OF RUPTURE OF PC CAST AT 70°F (21°C)[a]

% BzP	% DMPT	Work Time (min)	Set Time (min)	Peak Exotherm (°F)	f_r (psi)	Average f_r (psi)
			31	125	2261	
2.0	1.0	9	31	124	2244	2214
			31	123	2138	
			36	126	2364	
1.5	0.75	12	38	124	2250	2220
			37	119	2048	
			43	126	2250	
1.25	0.625	16	43	124	2244	2237
			43	120	2216	
			50	124	2166	
1.0	0.50	21	51	118	2100	2132
			51	115	2132	

[a]NOTES:

Monomer: 95% MMA + 5% TMPTMA
Specimen Size: 2-inch x 2-inch x 12-inch (51-mm x 51-mm x 305-mm) beam
Temperature of Specimen when mechanically tested: 70°F (21°C)
PC density: 136.6 pcf (2188 kg/m^3)
Monomer loading: 26.2% by vol; 11.5% by wt.
PC age when tested: 24 hr.

TABLE 6. MODULUS OF RUPTURE OF PC CAST AT 50°F (10°C)[a]

% BzP	% DMPT	Work Time (min)	Set Time (min)	Peak Exotherm (°F)	f_r (psi)	Average f_r (psi)
			41	97	2543	
2.75	1.375	12	41	98	2441	2411
			41	94	2250	
			45	99	2177	
2.25	1.125	13	45	95	2205	2210
			46	91	2250	
			54	101	2125	
1.75	0.875	18	54	100	2194	2183
			54	98	2233	
			72	89	2216	
1.25	0.625	34	72	85	2025	2070
			72	84	1969	

[a]NOTES:

Monomer: 95% MMA + 5% TMPTMA
Specimen Size: 2-inch x 2-inch x 12-inch (51-mm x 51-mm x 305-mm) beam
Temperature of Specimen when mechanically tested: 70°F (21°C)
PC density: 136.6 pcf (2188 kg/m³)
Monomer loading: 26.2% by vol; 11.5% by wt.
PC age when tested: 24 hr.

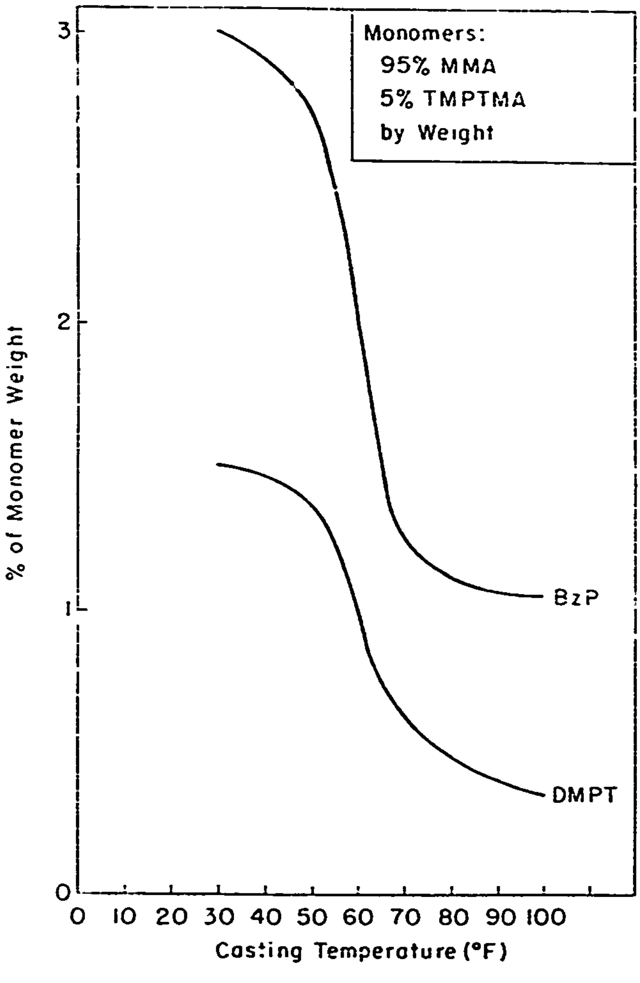


Fig. 10. BzP and DMPT Levels in the Monomer Formulations Which Yielded the Highest Average Moduli of Rupture Versus Casting Temperature

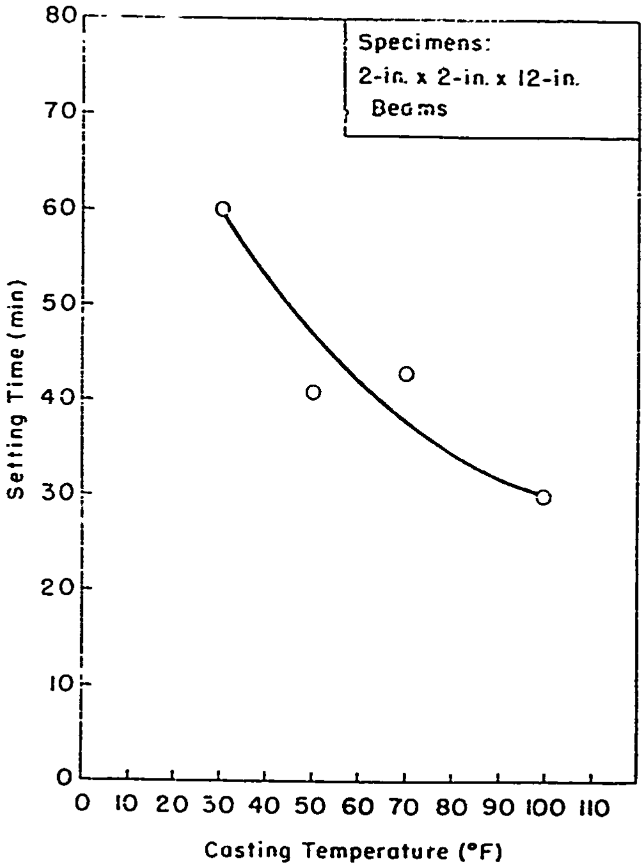


Fig. 11. The Setting Time of the Polymer-Concrete Mixes Which Correspond to the PC Highest Average Moduli of Rupture Versus Casting Temperature

a smooth surface. The specimens were tested at a loading rate of 47.16 psi/second (sec) in the elastic range. Table 7 and Figure 12 summarize the results. Specimens cast at 70° and $100^{\circ}F$ failed in a ductile manner; however, the specimen cast at $30^{\circ}F$ exploded at ultime load which is characteristic of very brittle behavior.

The effect of casting temperature on the flexural bond strength of PC to portland cement concrete (PCC) was investigated. Nine PCC beams 2-inch x 2-inch x 12-inch were cast using a low water-cement ratio. The mix design is given in Figure A-2, Appendix A. The specimens were cured in a moist room for six days. Six of the beams were cut at midspan using a diamond-tipped saw. The sawed beams and the three remaining uncut beams were placed in an oven at $250^{\circ}F$ for 48 hours to dry. Each of the 12 beam halves was placed back in its mold in the environmental chamber, which was set at the desired casting temperature. After 24 hours, PC was cast in the empty half of each mold using the promoter and initiator levels given in Figure 1. Thermocouples were used to measure the exotherms. It was observed that the setting times and peak exotherms of the PC were almost identical to those of the beams prepared during the optimization program. After 10 hours curing in the environmental chamber, the beams were maintained at room temperature for 14 hours. The 12 PC-PCC beams and the three uncut PCC beams were placed in an oven at $136^{\circ} \pm 4^{\circ}F$ for 24 hours.

TABLE 7. PROPERTIES OF THE COMPRESSIVE STRENGTH SPECIMENS CAST AT DIFFERENT TEMPERATURES[a]

Series	Casting Temp. (°F)	% BzP	% DMPT	Setting Time (min)	Peak Exotherm (°F)	Compressive Strength (psi)	Average Compressive Strength (psi)	E (psi)
PC-30	30	3.0	1.5	58 58 59	101 99 90	9479 9762 9012	9418	1.66×10^6
PC-70	70	1.25	0.625	39 39 40	160 162 165	6890 7017 6791	6899	1.32×10^6
PC-100	100	1.05	0.35	27 27 26	169 170 173	6791 7130 7597	7173	1.49×10^6

[a]NOTES:

Monomers: 95% MMA, 5% TMPTMA
Monomer Loading: 26.2% by vol; 11.5% by wt.
Density: 136.6 pcf (2.88 kg/m^3)
Specimens: 3-inch x 6-inch (76-mm x 152-mm) cylinders
Testing temperature: 70°F (21°C)
Age: 24 hr.
Loading Rate: 47.16 psi/sec. (6.325 MPa/sec)

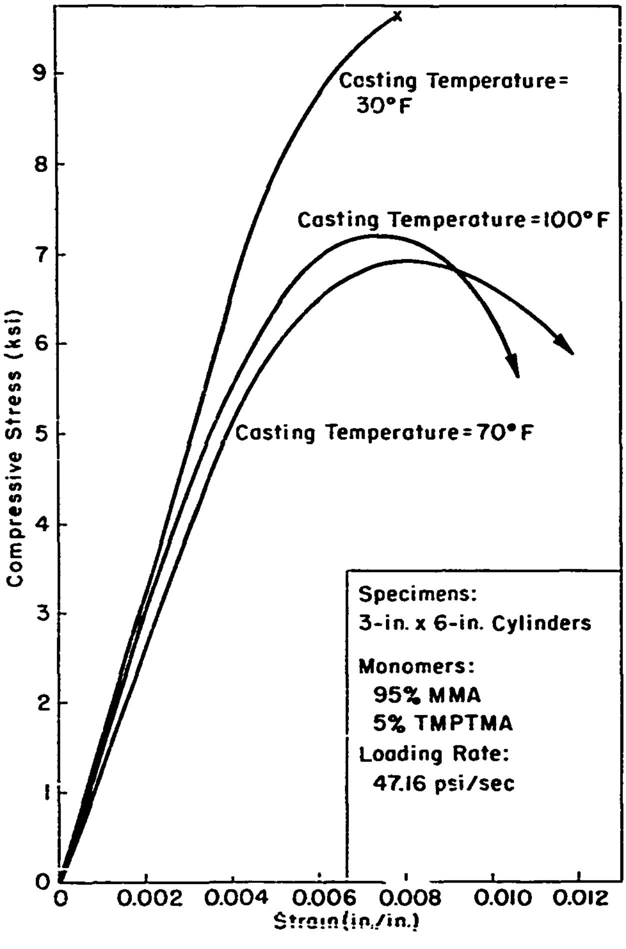


Fig. 12. Effect of Casting Temperature on PC Compressive Behavior

The beams were then tested as shown in Figure 13. The uncut beams were used as control specimens. The test results are given in Table 8. With the exception of the beams cast a 100°F, all beams failed at about 600 psi or higher. It should be noted that these tests, in which PC was bonded to sawed faces of the PCC, would be expected to yield lower values than would normally be expected for concrete in which all or part of the interface would be a broken surface.

The bond of PC to PC was also studied. Both vertical cold joints (Figure 14) and horizontal cold joints (Figure 15) were tested. Half the beam was cast with PC; six days later the other halves of the beams were cast. The vertical cold joint was formed with sheet metal which resulted in a smooth interface. Aggregate was Colorado River silicious sand (Table A-3, Appendix A). The beams were tested when the first pour was 7 days old and the second pour was 1 day old. The results are summarized in Table 9. All specimens failed in flexure. Those with vertical joints failed a few millimeters inside the new PC at an average flexural stress of 945 psi. The tests of control specimens indicated that there was only about 3 percent greater strength for 7-day-old PC than 1-day-old PC. At the ultimate load, the shear stress for the specimens with horizontal cold joints was greater than 240 psi.

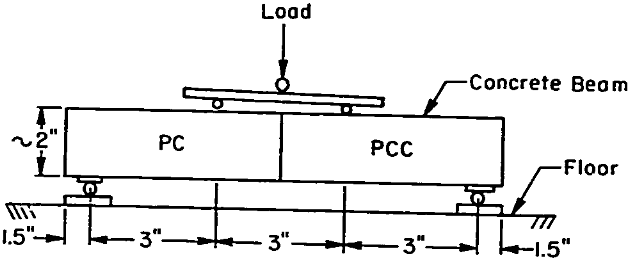


Fig. 13. Test Set-Up for PC-to-Portland Cement Concrete Flexural Bond Strength

TABLE 8. THE EFFECT OF CASTING TEMPERATURE ON THE MINIMUM POLYMER CONCRETE - PORTLAND CEMENT CONCRETE FLEXURAL BOND STRENGTH[a]

PC Casting Temp. (°F)	% BzP	% DMPT	Test Temp. (°F)	f_r (psi)	Average f_r (psi)	Mode of Failure
100	1.05	0.35	138 138 137	360 371 366	366	Interface
70	1.25	0.625	139 138 138	596 641 557	598	PCC
50	2.75	1.375	137 137 138	815 939 731	828	PCC
30	3.0	1.5	139 139 138	900 968 923	930	PCC
Control PCC Specimens				939 963 951	951	Note: Coarse Aggregate Failed

[a]NOTES:

Monomers:
95% MMA
5% TMPTMA

Specimens:
2-inch x 2-inch x 12-inch

Age when tested:
48 hours

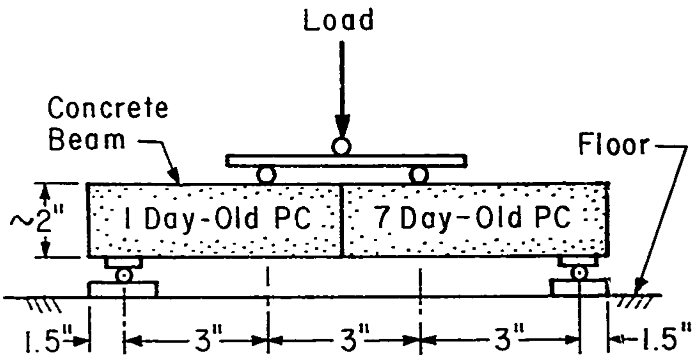


Fig. 14. Test Set-Up for Flexural Strength of Vertical Bond

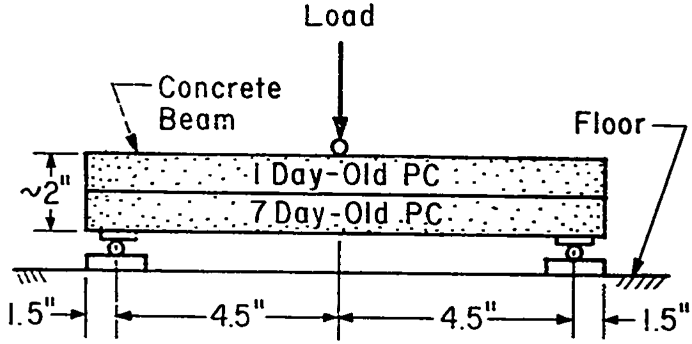


Fig. 15. Test Set-Up for Flexural Strength of Horizontal Bond

TABLE 9. TEST RESULTS OF PC TO PC BOND STRENGTH

	f_r (psi)	Average f_r (psi)
A - Beam with a Vertical Cold Joint at Midspan-Third Point Loading	939 894 1029	945
B - Beams with a Horizontal Cold Joint at Middepth-Single Point Loading	2093 2227 2152	2157
7-day-old PC Control Specimens	2076 1974 1991	2014
1-day-old PC Control Specimens	1536 2014 2306	1952

2.2.2 Effect of Testing Temperature and Loading Rate. The effect of testing temperature was found from flexural tests of 2-inch x 2-inch x 12-inch beams loaded at third-points with a 9-inch span. The aggregate gradation used in the tests is given in Table A-1. The beams were cast at 70°F and left for 10 hours. Three specimens were maintained at each testing temperature of 0°, 70°, and 137°F for 14 hours prior to testing. Results are given in Table 10 and Figure 16. Compared to a testing temperature of 70°F, the strength was 12 percent higher for 0°F and 6 percent lower for 138°F, which is about the maximum surface temperature that a runway would reach if the ambient air temperature were 100°F.

The effects of testing temperature and loading rate on compressive strength were investigated using 3-inch x 6-inch cylinders cast at 70°F using the aggregate gradation given in Table A-1. After being sawed, specimens were maintained at the testing temperature for 14 hours. Three specimens at each testing temperature were loaded at a rate of 47.16 psi/sec, and three were loaded at 23.58 psi/sec. These loading rates are within the tolerance permitted by ASTM C-39. Table 11 and Figures 17 to 19 present the results. Relative strength in Table 11 corresponds to the ratio of the average strength for each set of three specimens to the average strength of all the specimens tested at 70°F. Similarly, the relative stiffness corresponds to the ratio of the stiffness calculated for each

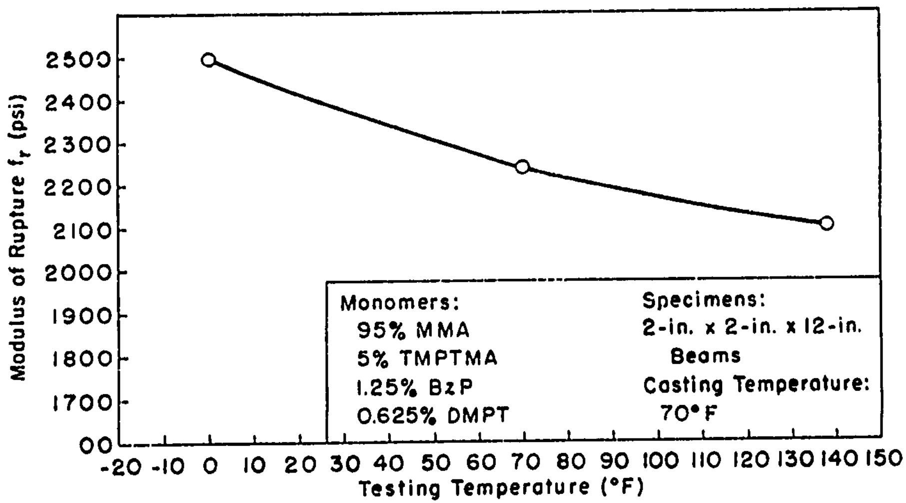
TABLE 10. EFFECT OF TESTING TEMPERATURE ON FLEXURAL STRENGTH OF POLYMER CONCRETE[a]

Testing Temperature (°F)	Modulus of Rupture f_r (psi)	Average f_r (psi)	Relative f_r	Type of Failure
0	2717 2475 2295	2496	1.116	Through most of coarse aggregate
70	2250 2244 2216	2237	1.0	Through most of coarse aggregate
138	1912 2160 2216	2096	0.937	Very few failure planes in coarse aggregate

[a]NOTES:

Monomer Formulation:
95% MMA
5% TMPTMA
1.25% BzP
0.625% DMPT

Casting Temperature: 70°F (21°C)
Specimens: 2-inch x 2-inch x 12-inch (51-mm x 51 mm x 305-mm) beams
Age when tested: 24 hours
PC density: 136.6 pcf (2188 kg/m^3)



Fi, 6. The Variation of the Average Modulus of Rupture with the Testing Temperature

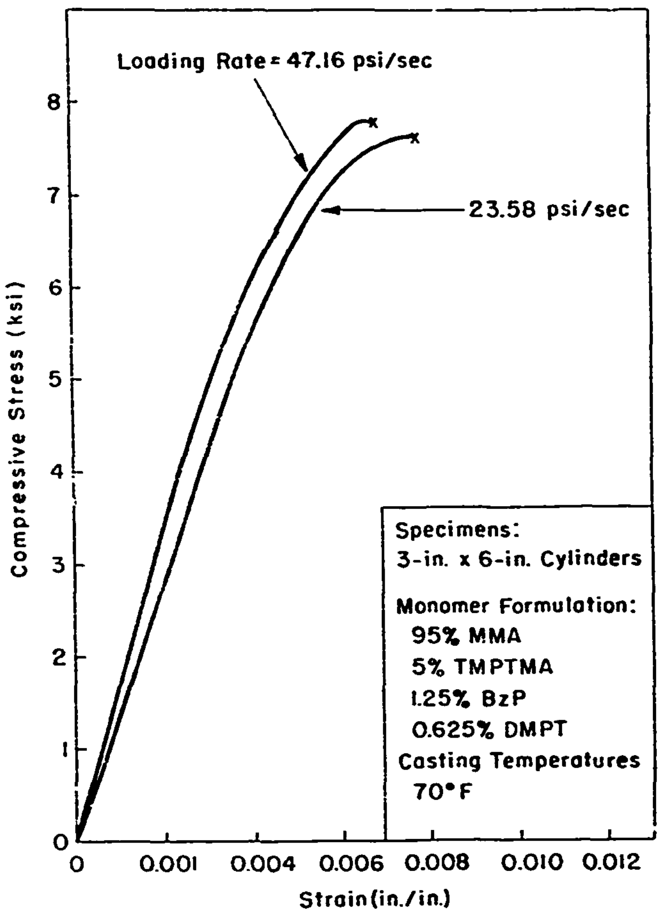


Fig. 17. Effect of Loading Rate on PC Tested at 0°F

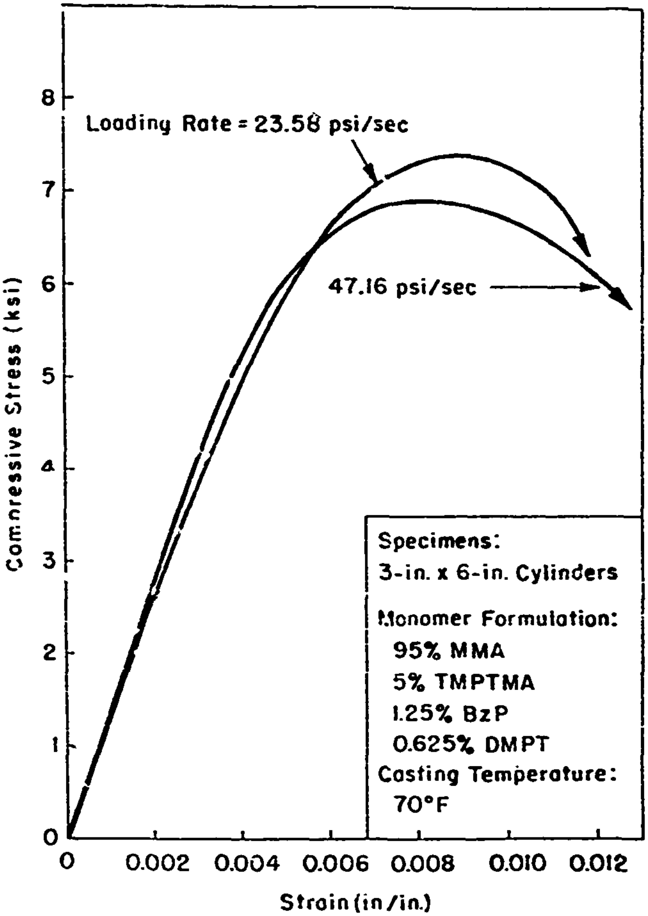


Fig. 18. Effect of Loading Rate on PC Tested at 70°F

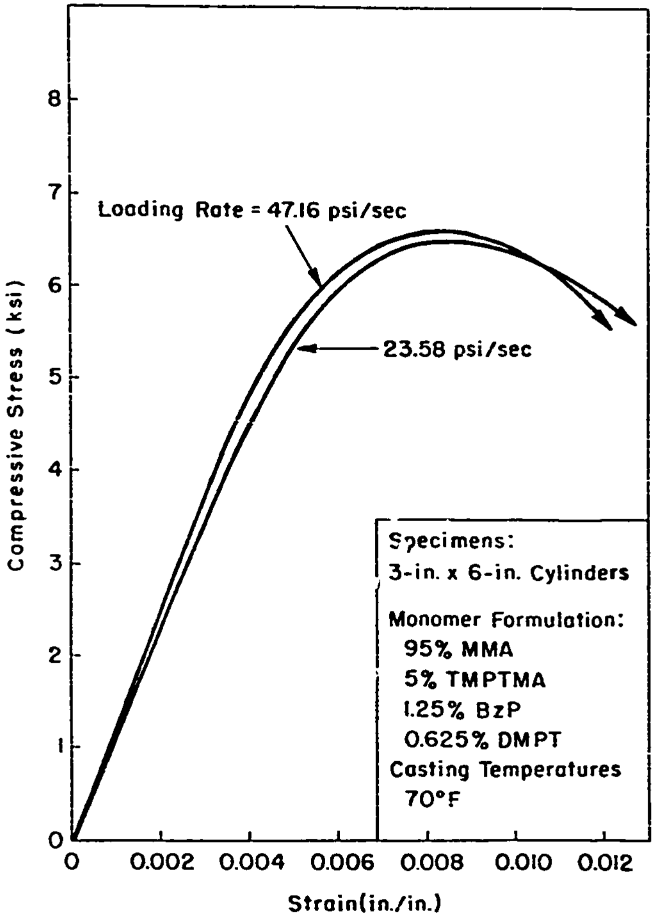


Fig. 19. Effect of Loading Rate on PC Tested at 138°F

TABLE 11. EFFECT OF TESTING TEMPERATURE AND LOADING RATE ON THE COMPRESSIVE PROPERTIES OF POLYMER CONCRETE[a]

Testing Temp. (°F)	Loading Rate (psi/sec)	Strength (psi)	Average Strength (psi)	E (psi)	Relative Strength	Relative Stiffness
0	47.16	7427 7682 8304	7804	1.52×10^6	1.089	1.172
	23.58	7781 7413 7639	7611	1.39×10^6	1.063	1.075
70	23.58	7074 7328 7880	7427	1.27×10^6	1.037	0.982
	47.16	6890 7017 6791	6899	1.32×10^6	0.963	1.018
138	47.16	6182 6776 6833	6597	1.23×10^6	0.921	0.950
	23.58	6394 6861 6211	6489	1.23×10^6	0.906	0.910

[a]NOTES:

Monomer Formulation: 95% MMA
5% TMPTMA
1.25% BzP
0.625% DMPT
Casting Temperature: 70°F (21°C)
Age when Tested: 24 hours
Monomer Loading: 26.27 by volume; 11.5% by weight
Specimens: 3-inch x 6-inch (76-mm x 152-mm) cylinders

set to the average of the stiffnesses of the two sets tested at 70°F. The specimens tested at 138°F and 70°F failed in a ductile manner, but those tested at 0°F failed in a brittle manner, and the failure was explosive.

2.3 MMA/TTEGDA PC System

Several monomers were investigated with the objective of providing additional ductility to the PC. Butyl acrylate has been used by many researchers to provide ductility, but its value is questionable (subsection 2.1.2).

Several monomer formulations were used to make 3-inch x 3-inch x 14-inch beams and 3-inch x 6-inch cylinders. Aggregate consisted of 50 weight percent all purpose sand and 50 weight percent 3/8-inch maximum size crushed limestone. Gradations are given in Table A-4. The beams were tested under third-point loading with a 12-inch span. The test was adapted from ASTM C78. Compressive strength was determined using a test adapted from ASTM C39; modulus of elasticity was determined using ASTM C469. The test for splitting tensile strength was adapted from ASTM C496.

Mechanical properties for different monomer formulations are given in Table 12. Stress-strain curves are shown in Figures 20 to 22. Figure 20 indicates that 10 percent BA provides no apparent improvement in ductility over a 100 percent MMA system. The ultimate strains for the two materials are

TABLE 12. MECHANICAL PROPERTIES OF PC FOR VARIOUS MONOMER SYSTEMS[a]

MMA	TMPTMA	TTEGDA	BA	EHMA	BzP	DMPT	Peak Temperature, °F	Compressive Strength, psi	Splitting Tensile Strength, psi	Modulus of Rupture, psi	Modulus of Elasticity, 10^6 psi	Ultimate Strain, in/in	Time to Peak Temperature of Cure, min.
100					1.33	0.7	117	8360	1230	1890	2.8	0.0057	81
95	5				1.33	0.7	149	8080	1300	1940	2.1	0.0080	40
95	5				1.33	0.7	149	8000	1210	1870	---	---	40
97.5		2.5			1.33	0.7	153	7140	1160	1670	2.3	0.0055	60
95		5			1.33	0.7	144	9620	1300	1930	2.5	0.0076	63
90		10			1.33	0.7	143	9330	1270	1840	2.6	0.0073	51
90			10		1.33	0.7	123	8360	1280	2020	3.0	0.0055	94
90				10	1.33	0.7	116	7610	1210	1760	3.0	0.0046	85
80				20	1.33	0.7	134	5750	1114	1840	2.0	0.0057	74
70				30	1.33	0.7	111	6890	1065	1670	2.6	0.0052	67
85		5		10	1.33	0.7	126	8930	1310	1850	2.6	0.0078	65
85		5		10	1.33	0.7	139	9790	1300	2070	3.0	0.0060	64
85		15			1.33	0.7	161	8610	1160	1870	2.5	0.0069	37
80		20			1.33	0.7	176	8850	1100	1890	2.8	0.0066	30

[a]Monomers are expressed as 100 percent of formulation; BzP and DMPT percentages are based on monomer weight.

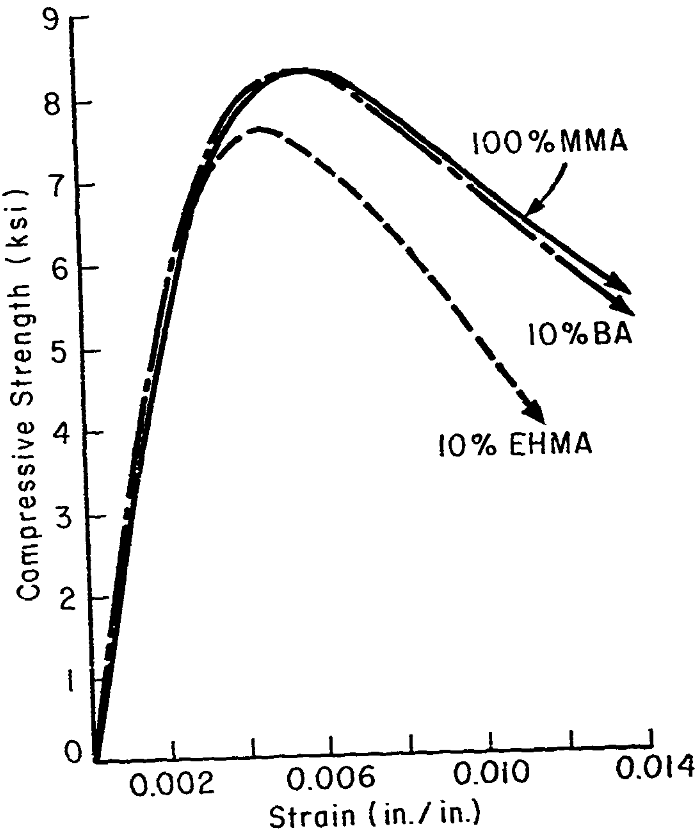


Fig. 20. Stress-Strain Curves Showing Effect of BA and EHMA

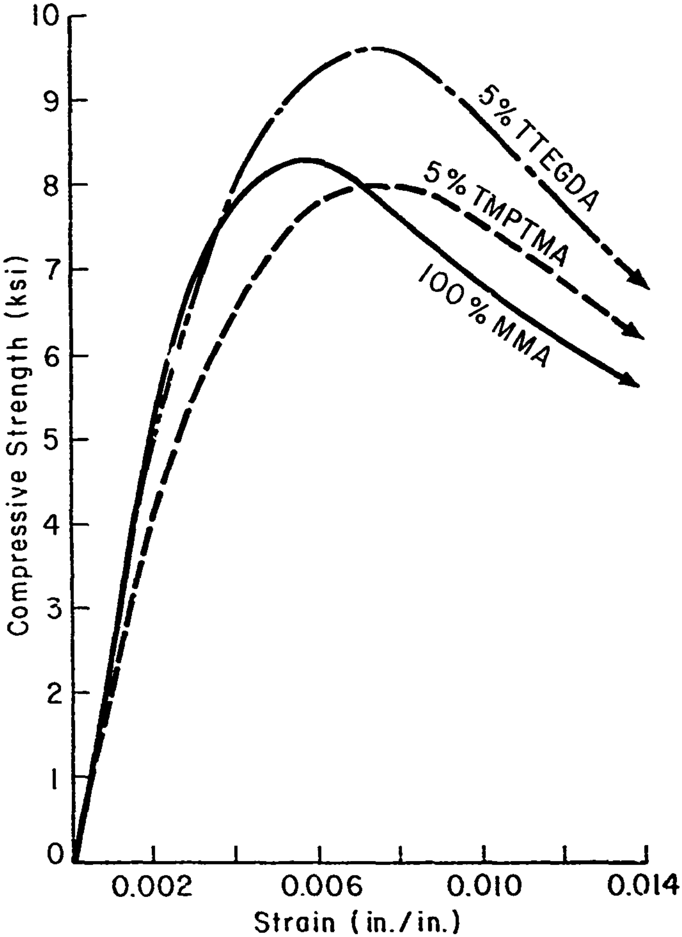


Fig. 21. Stress-Strain Curves Showing Effect of TTEGDA and TMPTMA

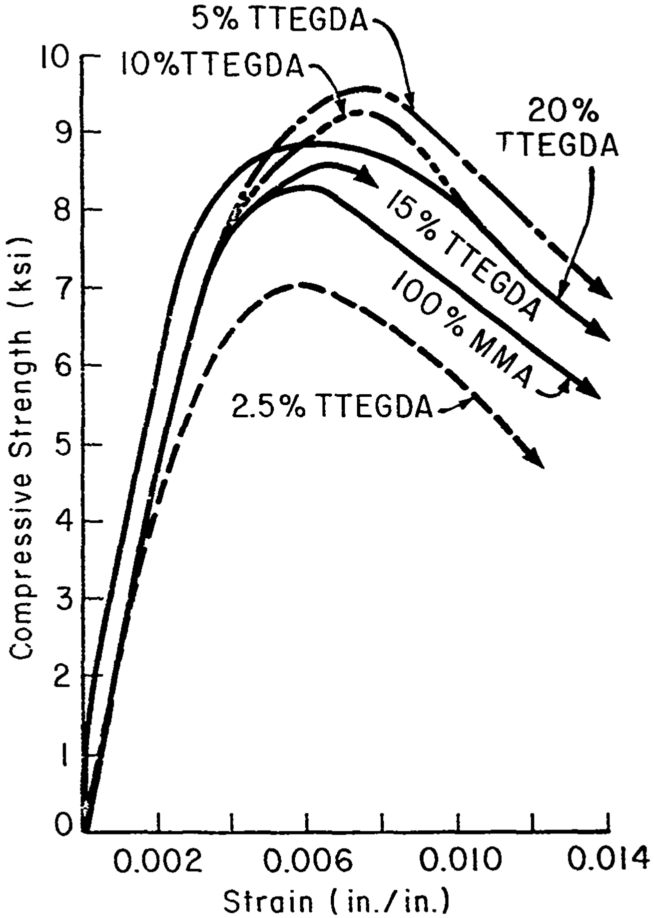


Fig. 22. Compressive Strength of PC Made with Varying Percentages of TTEGDA

nearly the same (Table 12). The monomer system of 90 percent MMA and 10 percent EHMA results in lower strength and reduced ultimate strain. The cross-linking agent TTEGDA is compared with TMPTMA in Figure 21. Compressive strength with 5 percent TTEGDA was 10 percent higher than for PC with 5 percent TMPTMA, although splitting tensile strength and modulus of rupture were the same. Figure 22 shows the difference in stress-strain behavior for MMA/TTEGDA systems with TTEGDA varying from 0 to 20 percent. The variation in behavior was not great, but 5 percent TTEGDA yielded the greatest compressive strength and modulus of rupture.

Since no results have been previously published on MMA/TTEGDA monomer systems, a systematic study was undertaken to determine the optimum initiator, promoter, and TTEGDA to produce setting times of one hour or less. Tables 13 to 16 give the results of studies made at -25°, 0°, 30°, and 60°F. Two 3-inch x 6-inch cylinders were cast after the molds, chemicals, and aggregate had been allowed to reach equilibrium temperature in the environmental chamber. The aggregate gradation is given in Table A-5. In these studies the monomer was 70 percent MMA and 30 percent TTEGDA. The time to peak exotherm, t_{pe}, and the flexural strength, f_r, are given in Tables 13 to 16. Specimens were tested at room temperature. Figures 23 to 26 give the variations of f_r and t_{pe} as a function of the percentages of DMPT and BzP and temperature at casting.

TABLE 13. EFFECT OF INITIATOR AND PROMOTER LEVELS ON PC PROPERTIES AT -25°F AMBIENT CASTING TEMPERATURE[a]

BzP (%)	DMPT (%)	t_{pe}[c] (min)	f_r[d] (psi)
3	3	240	1344
3	6	155	1248
3	8	139	1146
3	12	119	768
4	4	160	1377
4	6	116	1094
4	8	117	992
4	10	101	881
4	12	96	679
5	8	102	800
5	10	88	714
5	12	80	518
6	4	140	1055
6	6	104	932
6	8	76	658
6[b]	12	105	470
6[b]	14	93	374
7[b]	4	174	894
7[b]	7	137	719
7[b]	10	112	542
7[b]	14	91	360

[a] 70% MMA, 30% TTEGDA

[b] -33°F

[c] time to peak exotherm

[d] modulus of rupture

TABLE 14. EFFECT OF INITIATOR AND PROMOTER LEVELS ON PC PROPERTIES AT 0°F AMBIENT CASTING TEMPERATURE[a]

BzP (%)	DMPT (%)	t_{pe} (min)	f_r (psi)
1	2	262	1677
2	2	143	1398
2	4	88	1312
2	6	73	1206
3	2	102	1280
3	3	84	1243
3	6	58	1137
3	8	51	908
4	2	124	1297
4	4	57	1159
4	6	47	922
4	8	44	713
4	10	42	696
5	2	89	1243
5	5	52	1039
5	8	46	740
5	10	37	566
6	2	94	1205
6	4	59	997
6	6	46	914
7	2	90	1000
7	4	56	958
7	7	42	718

[a]70% MMA, 30% TTEGDA

TABLE 15. EFFECT OF INITIATOR AND PROMOTER LEVELS ON PC PROPERTIES AT +30°F AMBIENT CASTING TEMPERATURE[a]

BzP (%)	DMPT (%)	t_{pe} (min)	f_r (psi)
1	1	70	1211
1	2	48	1136
1	3	40	1089
2	1	43	1240
2	2	34	1228
2	4	25	979
2	6	28	603
3	2	31	1339
3	3	26	1259
3	6	20	759
3	8	15	428
4	2	36	1197
4	4	17	960
4	6	20	803
4	8	16	460
5	2	22	1129
5	5	14	859
5	8	14	462
6	2	17	1150
6	4	13	894
6	6	13	718

[a]70% MMA, 30% TTEGDA

TABLE 16. EFFECT OF INITIATOR AND PROMOTER LEVELS ON PC PROPERTIES AT +60°F AMBIENT CASTING TEMPERATURE[a]

BzP (%)	DMPT (%)	t_{pe} (min)	f_r (psi)
0.75	0.125	87	1173
0.75	0.25	53	1248
0.75	0.5	36	1231
1.0	0.25	45	1255
1.0	0.5	34	1265
1.0	2.0	21	613
2.0	0.5	18	1337
2.0	1.0	15	1235
2.0	2.0	12	1133
3.0	1.0	23	1243
3.0	2.0	9	1092
3.0	3.0	8	847
4.0	2.0	8	1134

[a]70% MMA, 30% TTEGDA

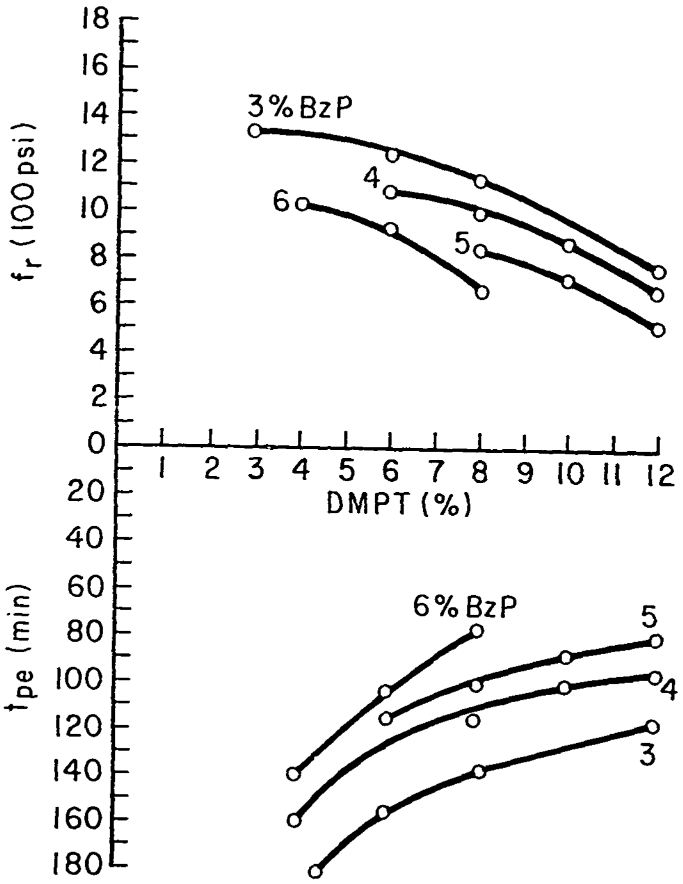


Fig. 23. Splitting Tensile Strength and Set Time for PC Cast at -25°F

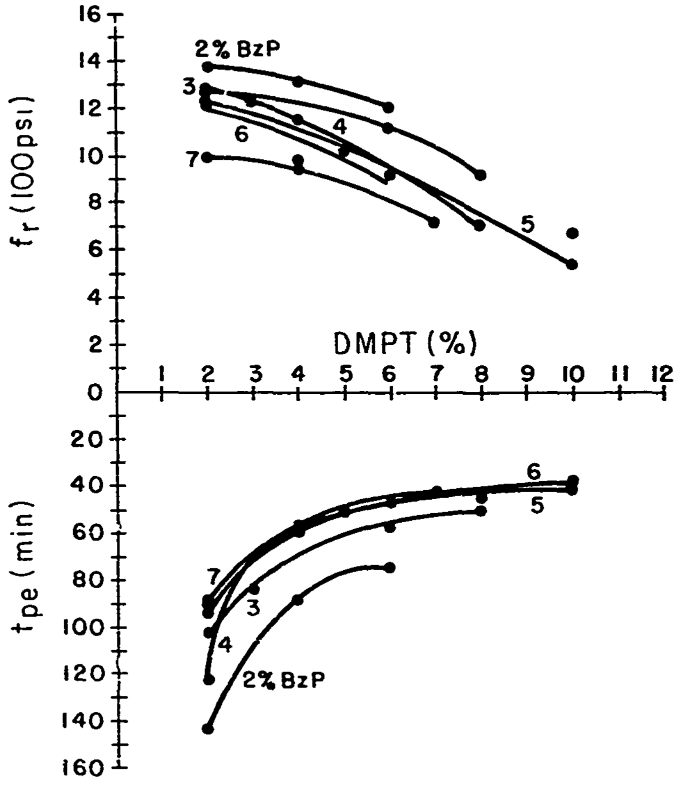


Fig. 24. Splitting Tensile Strength and Set Time for PC Cast at 0°F

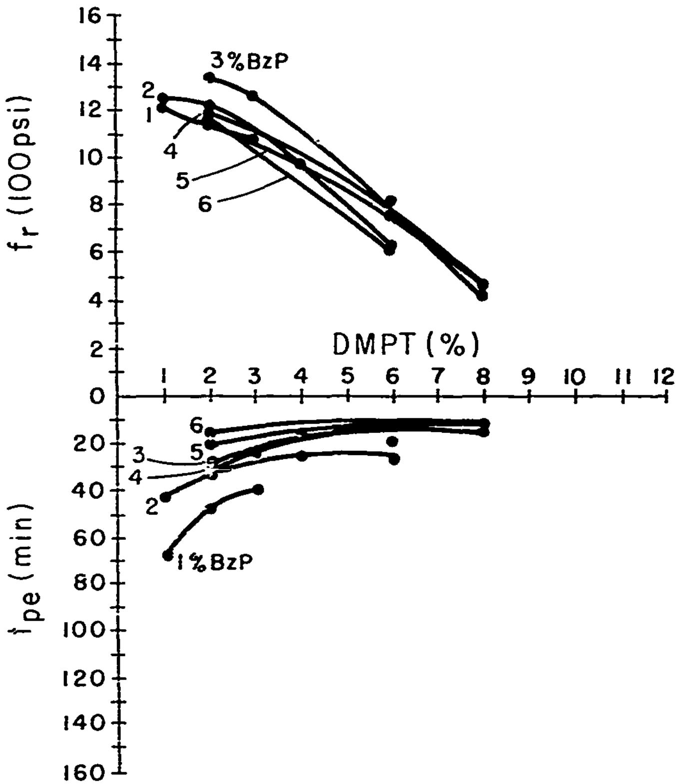


Fig. 25. Splitting Tensile Strength and Set Time for PC Cast at +30°F

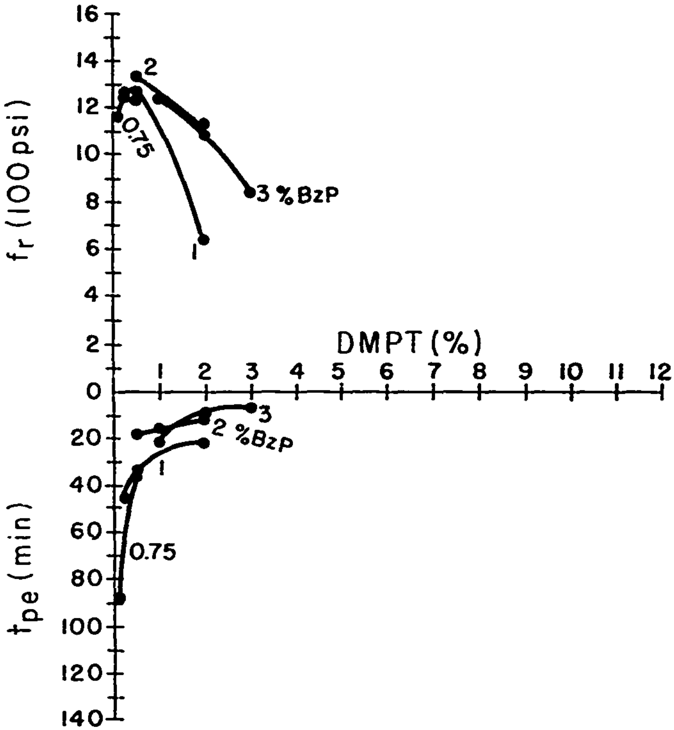


Fig. 26. Splitting Tensile Strength and Set Time for PC Cast at +60°F

Figures 27 and 28 give the optimum formulations for 70 percent MMA/30 percent TTEGDA to provide 20- to 60-minute set times and 20- to 120-minute set times, respectively.

The effect of percent TTEGDA on set time and mechanical properties is shown in Table 17. These tests were conducted at room temperature. The effect of monomer temperature on setting time is shown in Figure 29. The test was conducted in an environmental chamber at $-32^{\circ}F$. Steel molds and aggregate were allowed to equalize in temperature at $-32^{\circ}F$. The monomer system was taken into the chamber and mixed immediately, and two 3-inch x 6-inch cylinders were cast for each monomer temperature. Figure 29 indicates that the set time is strongly influenced by monomer temperature, and this suggests that if the monomer can be maintained at $50^{\circ}F$ or higher, the problem associated with low ambient temperatures is not nearly as difficult as when monomers are at ambient temperatures.

2.4 MMA Prepackaged System

2.4.1 Availability. There are several prepackaged MMA-based polymer concrete systems currently marketed in the U.S. and abroad. Silikal® is one of the most widely known PC systems, having been developed in West Germany in the early 1960's. It is currently sold in the U.S. under its own trade name and marketed under several other trade names by companies licensed to market the product. A special version, Silikal® R7/Bw, is

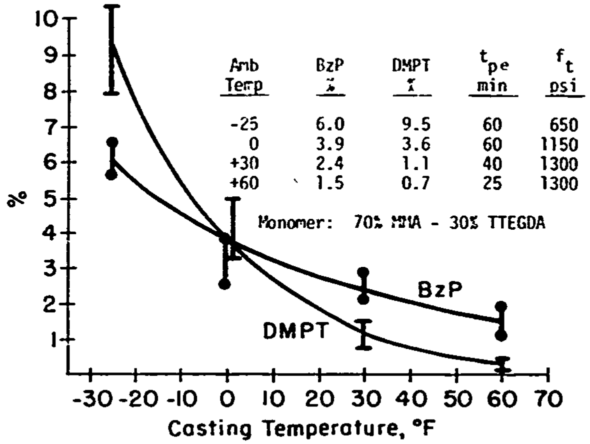


Fig. 27. Variation of Optimal Formulation with Casting Temperature to Yield a 20- to 60-min. Set Time

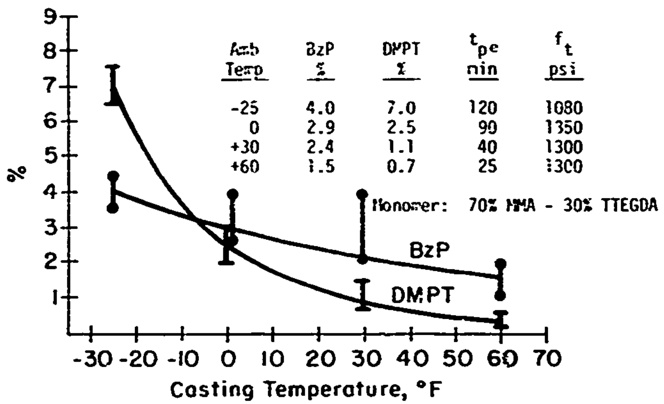
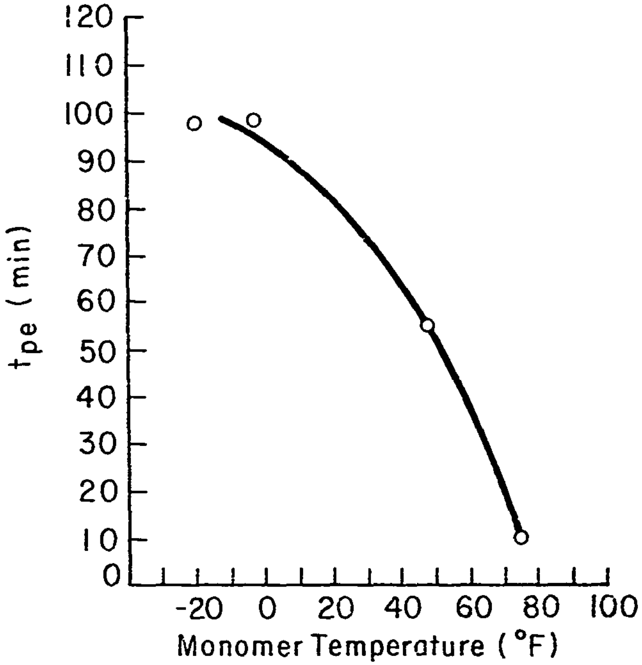


Fig. 28. Variation of Optimal Formulation with Casting Temperature to Yield a 20- to 120-min. Set Time

TABLE 17. EFFECT OF VARIATION OF PERCENT OF TTEGDA ON PC PROPERTIES[a]

MMA	TTEGDA	BzP	DMPT	P.E.	t_{pe}	f_c	f_{st}	f_r
95	5	1.33	0.7	144	63	9630	1300	1940
90	10	1.33	0.7	143	51	9340	1270	1840
85	15	1.33	0.7	-	37	8630	1168	1872
80	20	1.33	0.7	-	30	8771	1102	1891
60	40	1.00	0.5	176	21	7724	1146	1657
40	60	0.8	0.05	224	12	5913	909	1167

[a]Tests conducted at room temperature



Specimens:
3-in. x 6-in. Cylinders

Casting Temperature:
-32°F

Monomers:
70% MMA
30% TMPTMA

Aggregate Temperature:
-32°F

Fig. 29. The Variation of Set Time with Monomer Temperature

made only for the German army for bomb damage repair and is stockpiled at German bases. Dupont is currently marketing a PC system, Crylcon®, in the U.S.

MMA prepackaged systems consist of a liquid component which contains primarily MMA and a powder component which apparently contains fine aggregate, colorants, initiators, and other additives designed to improve the workability. The liquid and powder components can be mixed in plastic bags provided by the manufacturer or in a concrete mixer. The manufacturers also recommend that the PC can be extended by the addition of aggregate.

2.4.2 Typical Properties. Tests on one prepackaged system were conducted to determine material properties. Both mortar and aggregate-extended PC were used in the tests.

Compressive strength was found for the mortar (without additional aggregate) using 3-inch x 6-inch cylinders. The test method was adapted from ASTM C39. The specimens were capped to provide a smooth surface. The specimens were tested 24 hours after casting, and the strength averaged 6280 psi and the strain at ultimate averaged 0.0086 inches/inches. A typical stress-strain curve is shown in Figure 30.

Compressive strengths were found for the mortar extended with aggregate. Round, silicious pea gravel with a 3/8-inch nominal diameter was used in ratios of 0.3, 0.6, and 0.9 by

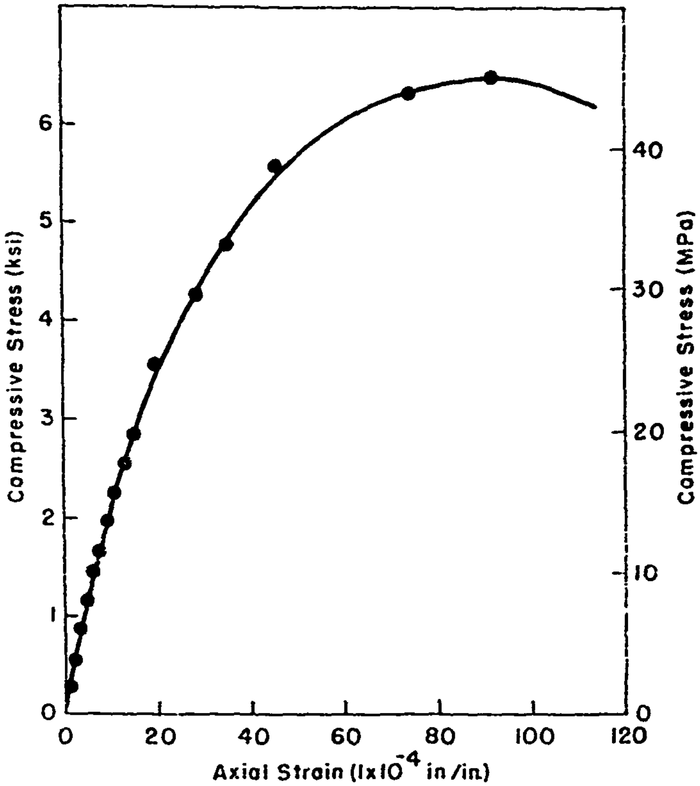


Fig. 30. Typical Stress-Strain Curve for Mortar System

weight of mortar. The compressive strengths averaged 5930, 6402, and 5480 psi, respectively. A typical stress-strain curve for the extended PC is shown in Figure 31.

Flexural strength was obtained using 3-inch x 3-inch x 16-inch beams made of mortar which were tested 24 hours after casting. The test method was adapted from ASTM C78. Loads were applied at the third-points of a 12-inch span. The modulus of rupture averaged 1975 psi.

Flexural bond strength tests were performed on beams made of PC bonded to PCC. PCC beams 3-inch x 3-inch x 16-inch were cast and cured for 7 days. A notch was sawed in the center of each beam prior to loading the beams to insure a break at mid-span. The beams were dried at 225°F for two days and cooled to room temperature.

The PCC halves were placed in molds, and PC was cast to form a full length beam. Some of the broken PCC faces were primed with primer furnished by the manufacturer, and flexural bond strengths were found using primed and unprimed beams made with PC mortar and extended mortar. All beams made with a 1:2:1 weight ratio of aggregate to mortar broke upon removal from the molds. The beams with primed surfaces developed strengths of 540 and 710 psi flexural strengths for aggregate-to-mortar ratios of 0 and 0.6, respectively. Beams without primed surfaces developed strengths of 245 and 350 psi strengths for ratios of 0 and 0.6. The beams with primed surfaces

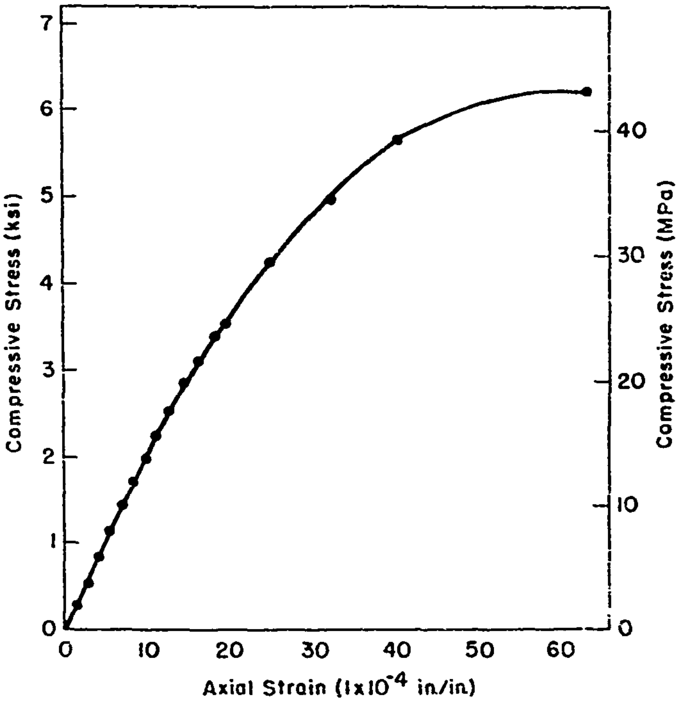


Fig. 31. Typical Stress-Strain Curve for Extended PC

maintained 100 percent bond at the interface with failure occurring in the PCC. Beams made with extended PC failed at higher strengths than beams made with mortar. It should be noted that flexural strengths were not as high as for the PCC beams when originally tested. This is a commonly-observed phenomenon and is attributed to the fact that microcracks that are produced during the first loading result in a weaker PCC when the beam is loaded the second time.

Splitting tensile strength was determined by a test adapted from ASTM C496 using 3-inch x 6-inch cylinders made with PC mortar and extended mortar. The results indicated that the extended PC specimens had higher strength for the four weight ratios of aggregate-to-mortar tested (0.3, 0.6, 0.9, and 1.2). The average tensile strength of all specimens made with extended PC was 950 psi, which was 14 percent higher than for the mortar alone.

2.5 Effect of Aggregate Type and Gradation

2.5.1 Aggregate Type. To study the effect of aggregate type and gradation on the mechanical behavior of polymer-concrete, 3-inch x 6-inch cylindrical specimens were prepared using three different aggregate mixes. Table 18 summarizes the properties of those mixes which were proportioned to yield the same monomer loading by volume as the mix used in the optimization program. A monomer formulation consisting of 95

TABLE 18. PROPERTIES OF THE AGGREGATE MIXES USED TO INVESTIGATE THE EFFECT OF AGGREGATE TYPE AND GRADATION ON POLYMER CONCRETE

Series	Coarse Aggregate		Aggregate Proportions	
	Type	SG (bulk)	%CA (by wt)	%FA[a] (by wt)
PC-T	3/8" Angular Trap Rock	3.07	65	35
PC-D	3/8" Angular Dolomite	2.67	65	35
PC-G	3/8" Longitudinal Granite	2.65	37	63

[a]Colorado sand - See Table A-3 for properties

percent MMA, 5 percent TMPTMA, 1.25 percent BzP, and 0.625 percent DMPT was used to cast the PC specimens at 70°F. This same formulation had yielded the highest average flexural strength for this casting temperature during the optimization program (Subsection 2.2.1). Table 19 summarizes the properties of the polymer-concretes produced and compares them with those of PC-70 (Table 7) using silicious sand (Table A-1). Figure 32 shows their respective stress-strain curves. In Table 19, the relative strength and stiffness are the ratios of the average strength and stiffness of each PC to those of PC-70 (Table 7). It was noticed when the failed specimens were inspected that, while the majority of the coarse aggregate located at the failure surface in PC-70 and PC-D-2 specimens failed along planes parallel to the applied load, very few had failed in PC-T-2 specimens. In PC-G-2 specimens, the coarse aggregate appeared to have failed along the polycrystalline planes. All the specimens failed in shear.

2.5.2 Aggregate Gradation. To investigate the effect of aggregate gradation on the setting time and mechanical behavior of polymer-concrete, four 3-specimen sets of 3-inch x 6-inch cylinders were cast. Three sets were made with single gradation Colorado sand. The fourth set was made with a three-part mix of the same sand. The specimens were named after the gradations of the sand used in each. The numbers refer to the sieves on which the aggregate was retained in the sieve analysis (Table

TABLE 19. VARIATION OF POLYMER CONCRETE PROPERTIES WITH AGGREGATE TYPE AND GRADATION[a]

Series	Density of PC (pcf)	Monomer Loading (%) Vol	Monomer Loading (%) wt	Peak Exotherm (°F)	Setting Time (min)	Compressive Strength (psi)	Average Strength (psi)	E (psi)	Relative Strength	Relative Stiffness
PC-70	136.6	26.2	11.5	160 162 165	39	6890 7017 6791	6899	1.32×10^6	1.0	1.0
PC-G-2	139.0	25.9	11.2	131 128 134	39	5715 6211 5659	5862	0.98×10^6	0.85	0.741
PC-D-2	139.0	26.0	11.2	133 130 129	43	6762 6055 6027	6281	1.46×10^6	0.910	1.102
PC-T-2	150.0	26.4	10.5	118 119 119	44	7356 6932 6904	7064	1.67×10^6	1.024	1.261

[a]NOTES:
Monomer Formulation: 95% MMA, 5% TMPTMA, 1.25% BzP, 0.625% DMPT
Specimens: 3-inch x 6-inch (76-mm x 152-mm) cylinders
Casting Temperature: 70°F (21°C)
Testing Temperature: 70°F (21°C)
Age when Tested: 24 hours
Loading Rate: 47.16 psi/sec (0.325 MPa/sec)

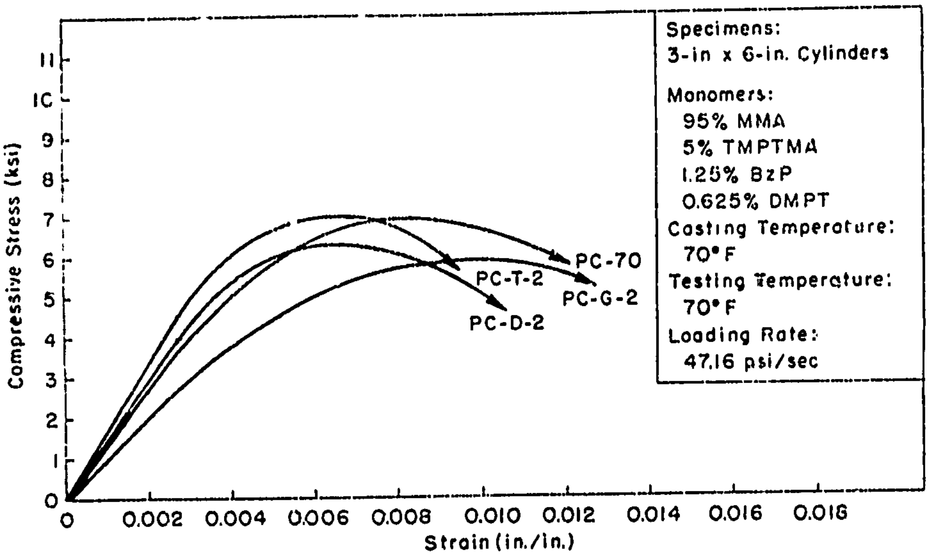


Fig. 32. The Effect of Aggregate Type and Gradation on PC Compressive Behavior

A-3). The casting temperature was 74°F. Because a relatively high monomer loading had been anticipated, the BzP and DMPT levels included in the monomer formulation were lower than those indicated by Figure 10. The formulation consisted of 95 percent MMA, 5 percent TMPTMA, 1 percent BzP, and 0.5 percent DMPT. To check for reproducibility, the casting was performed using one batch of the chemicals to cast each set of four specimens, which consisted of one specimen from each of the four 3-specimen sets. Table 20 summarizes the test results, and Figure 33 shows the average stress-strain curve for three of the five mixes.

Another series of tests was performed comparing the use of 2- to 3-inch size aggregate with 1/2- to 3/4-inch aggregate. User-formulated PC, and the Silikal® R7/BW provided by AFESC were used in the tests. Splitting tensile strength tests were performed on 6-inch x 12-inch cylinders and results are summarized in Figure 34.

2.6 Effect of Wet Aggregate

It is well known that the presence of excess water in the aggregate reduces the mechanical strength of MMA polymer concrete (Reference 4). The maximum amount of water permitted by specifications for MMA PC has generally been in the range of 0.5 to 1.0 percent. The maximum moisture content appears to be dependent upon several variables, including aggregate porosity and gradation of the aggregate. It would be expected that

TABLE 20. THE EFFECT OF VARYING THE AGGREGATE GRADATION ON POLYMER CONCRETE PROPERTIES[a]

Series[c]	PC Unit wt (PCC)	Monomer Loading[b] (%) by wt	Monomer Loading[b] (%) by vol	Specimen	Peak Exotherm (°F)	Setting Time (min)	Compressive Strength (psi)	Average Compressive Strength (psi)	E (psi)	Shape of Failure Surface
PC-S-(100)	116.0	24.7	47.9	A	163	49	7583	7516	0.837×10^6	Splitting
				B	168	49	7342			
				C	165	48	7625			
PC-S-(50)	119.2	22.6	44.9	A	188	39	7823	7512	0.915×10^6	Splitting
				B	192	38	7526			
				C	190	38	7187			
PC-S-(30)	119.5	22.4	44.6	A	196	39	6975	6975	0.994×10^6	Shear
				B	202	39	7017			
				C	200	38	6932			
PC-S-(T)[d]	123.5	17.4	35.9	A	192	37	6861	6725	1.14×10^6	Shear
				B	194	37	6706			
				C	198	36	6607			

[a]NOTES:

Monomer System: 95% MMA, 5% TMPTMA, 1% BzP, 0.5% DMPT
Casting Temperature: 74°F (23°C)
Testing Temperature: 70°F (21°C)
Age when Tested: 48 hours
Specimens: 3-inch x 6-inch (76-mm x 152-mm) cylinders
Loading Rate: 47.16 psi/sec (0.325 MPa/sec)

[b]Including 1.9% monomer absorption by weight by the aggregate

[c]Named after the sieve on which the sand was retained (see Table A-3)

[d]50% #16, 30% #8, 20% #50 sand

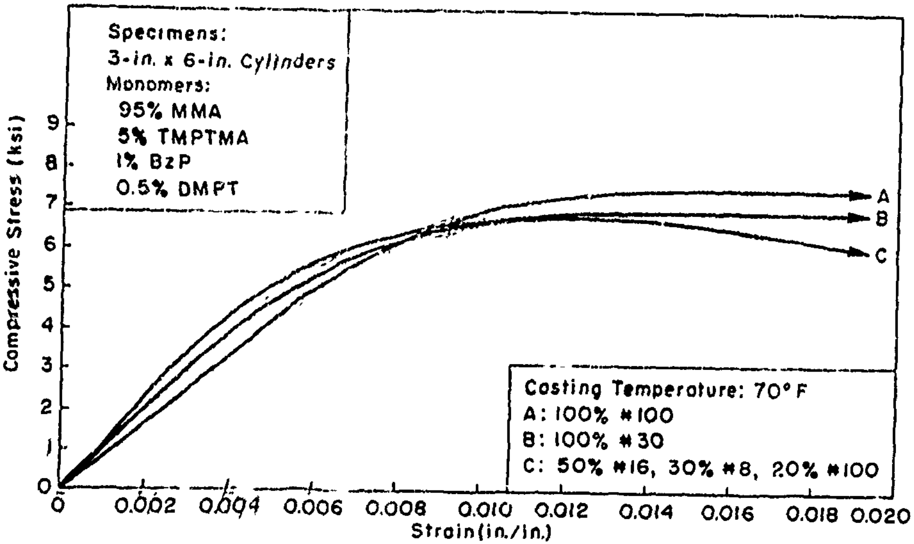


Fig. 13. The Effect of Aggregate Gradation on the Compressive Behavior of Polymer Concrete Made with Colorado River Sand

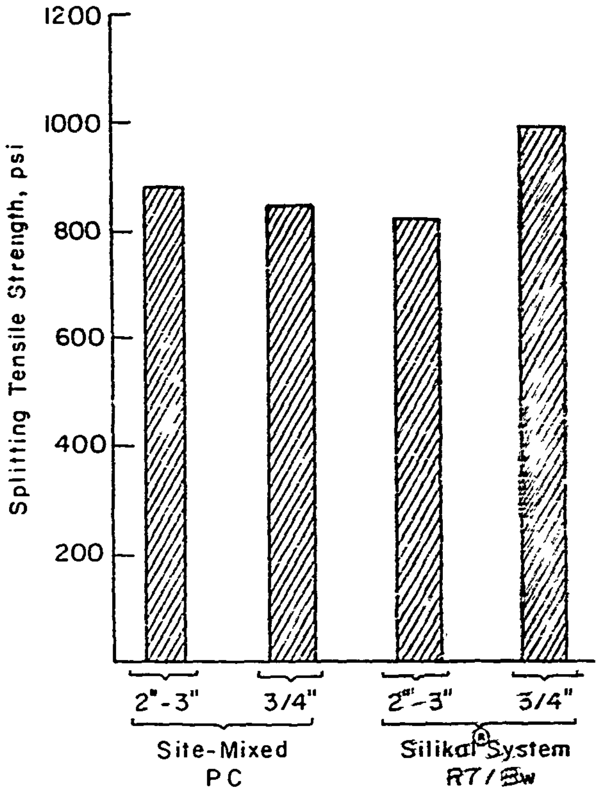


Fig. 34. Splitting Tensile Strength for Varying Aggregate Size and PC System

aggregate with a relatively high porosity would tolerate a higher moisture content since more water would be absorbed by the aggregate, which would reduce the free water in the pores. Similarly, for gradations containing a relatively high percentage of fines, the higher surface-to-volume ratio would permit more water to be absorbed by the aggregate.

To determine the effect of moisture in aggregate on the properties, compressive and split tensile tests were performed on 3-inch x 6-inch cylinders made of PC using 50 weight percent all-purpose sand and 50 weight percent 3/8-inch coarse aggregate. Both silicious and limestone coarse aggregates were used. The gradations and properties of the aggregates are shown in Table A-4. The specific gravities and water absorptions were found in accordance with ASTM C-127 and C-128. Aggregates used in all moisture tests were dried at $\sim 250^{\circ}F$ and cooled, and the aggregate was then soaked in water for 24 hours. The monomer formulation was 95 percent MMA, 5 percent TTEGDA, 1.33 percent BzP, and 0.70 percent DMPT. The results of the compressive strength tests and splitting tension tests for silicious coarse aggregate are shown in Figures 35 and 36. The silicious aggregate had a relatively low absorption value, and the strength was reduced very rapidly with increasing moisture content. For moisture contents in excess of 3 percent, it was difficult to remove the cylinders from the molds. Figures 37 and 38 give results for limestone coarse aggregate. The limestone aggregate

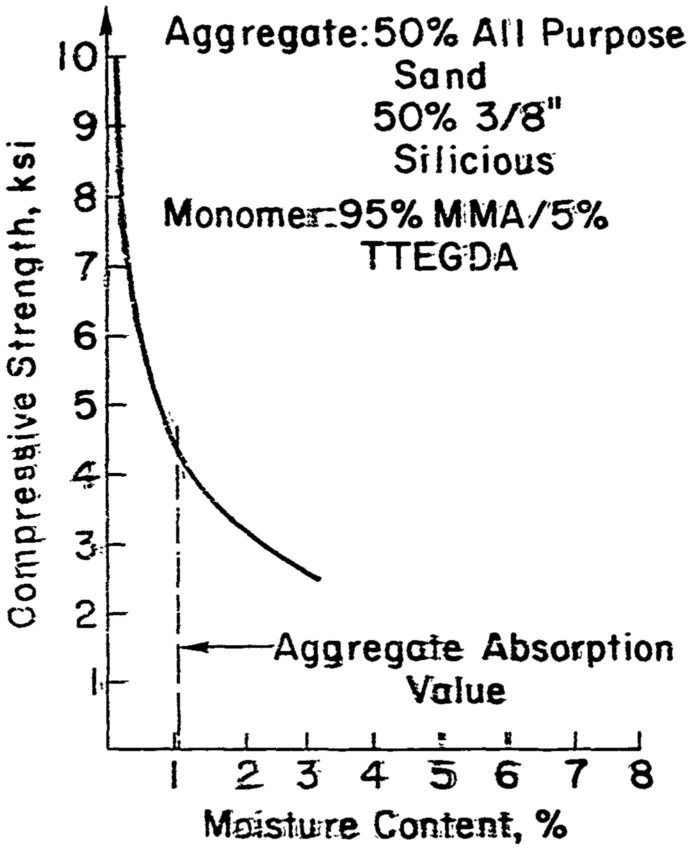


Fig. 35. Effect of Moisture on Compressive Strength of PC with Silicious Aggregate

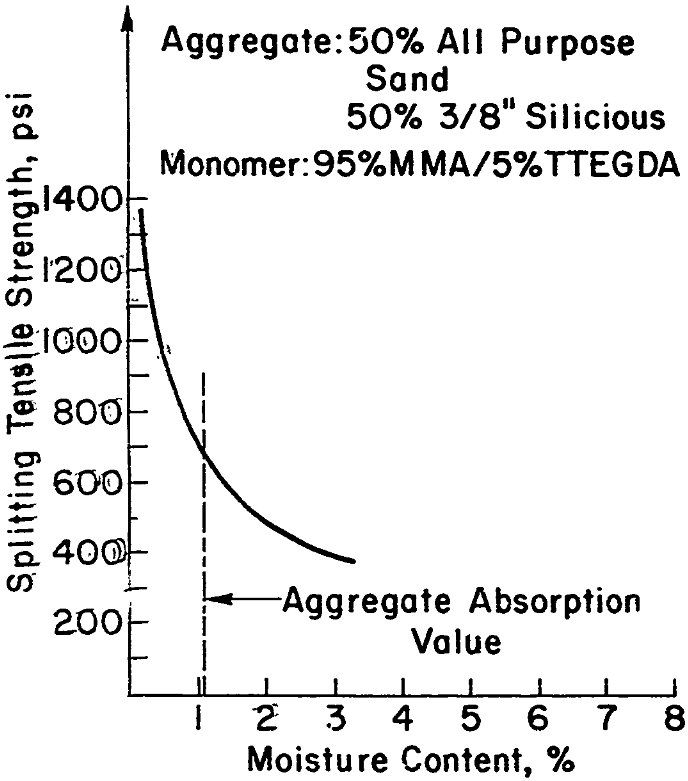


Fig. 36. Effect of Moisture on Splitting Tensile Strength of PC with Silicious Aggregate

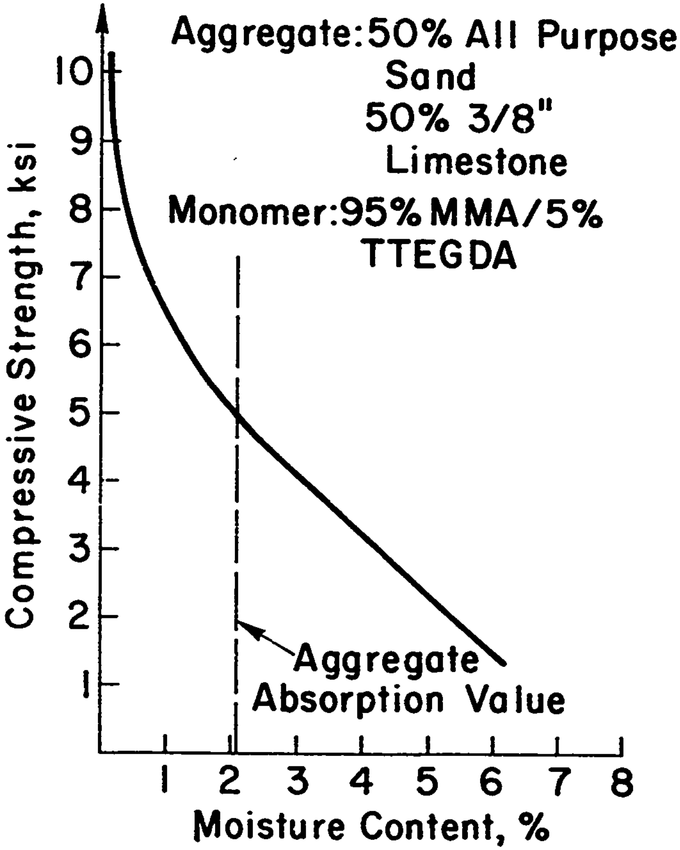


Fig. 37. Effect of Moisture on Compressive Strength of PC with Limestone Aggregate

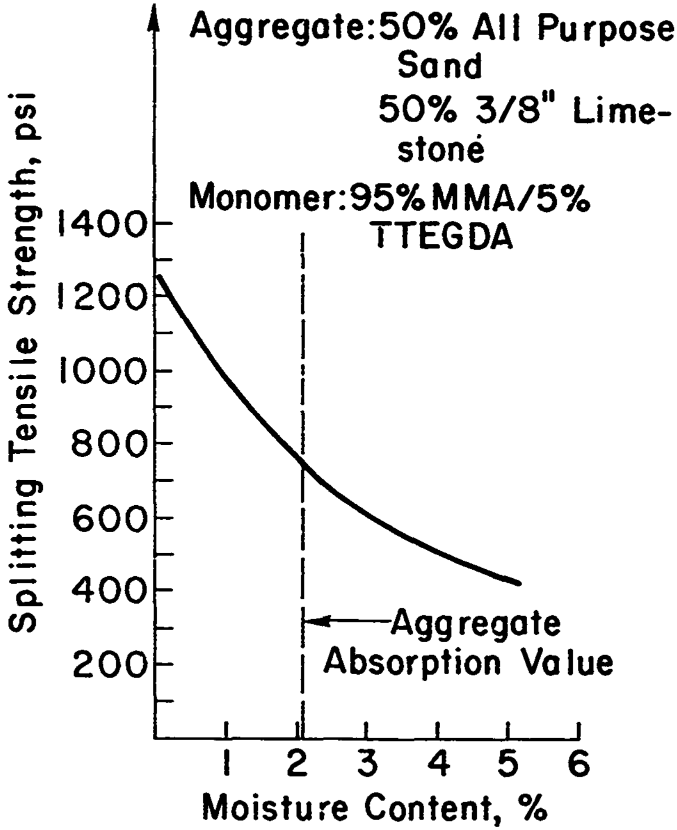


Fig. 38. Effect of Moisture on Splitting Tensile Strength of PC with Limestone Aggregate

has a higher absorption value than the silicious aggregate, which enables the PC to tolerate a higher moisture content.

Tests were also performed on Silikal® R7/BW, the special version for the German army, to determine the effect of moisture content. The PC was extended at the volume ratio of 1 part Silikal® to 1 part 1/2- to 1-inch coarse aggregate. Figure 39 indicates the splitting tensile strength for silicious and limestone aggregate. The moisture content was a function of the coarse aggregate. It should be noted that since the Silikal®-to-aggregate weight ratio was ~0.9:1, the moisture contents based on total weight would have been less than one-half those values shown.

Several methods were investigated to minimize the effects of moisture in aggregate: chemical additives in the monomer, aggregate treatment, and addition of fibers to the mix. The results of this investigation will be described.

2.6.1 Chemical Additives. The preferred solution would be an additive which, when added to the monomer, would insure good bond to the aggregate by negating the effect of the water. Considerable effort was expended to identify chemical additives from many sources: technical literature, MMA manufacturers, other chemical suppliers, and researchers at universities and laboratories. Many suggestions were received, including: acrylic acid (AA), methacrylic acid (MA), hydroxy propyl

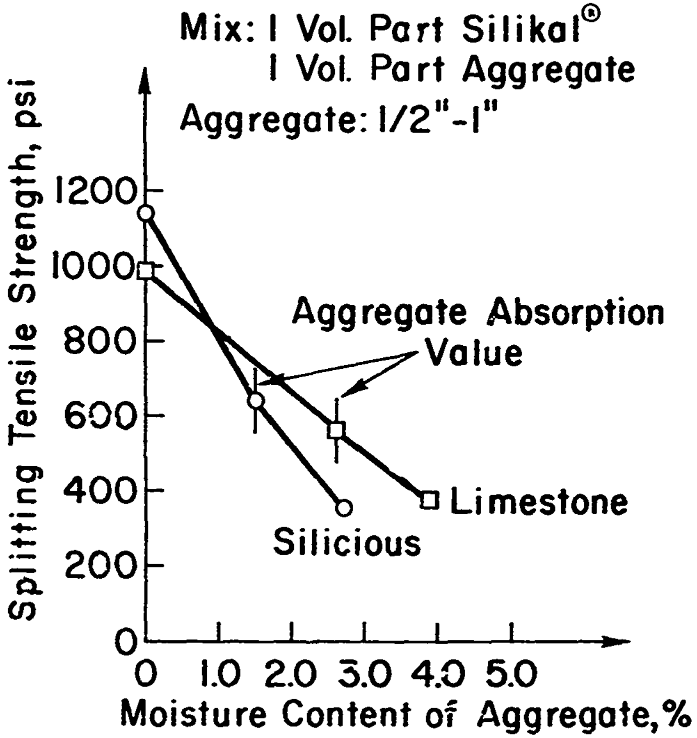


Fig. 39. Effect of Moisture on Splitting Tensile Strength of Silikal® R7/Bw

methacrylate (HPMA), TTEGDA, water soluble epoxies, and silane coupling agent.

Polymer concrete was made in the form of 3-inch x 6-inch cylinders using aggregate with 3 to 5 percent moisture content. A monomer system of 95 percent MMA and 5 percent TTEGDA was used with varying amounts of AA, MA, and HPMA added. Compressive strengths were obtained to provide a measure of effectiveness of the additives. Figure 40 summarizes typical results of these tests. The basic MMA/TTEGDA monomer provided the highest strengths. Some combinations of these additives reduced the strength by 50 percent or more. Higher percentages of AA and MA were used without success.

Silane coupling agent (SCA) has been used several ways to improve the bond between aggregate and polymer (Reference 5):

(1) Passing SCA vapors over aggregate.

(2) Adding SCA to MMA.

(3) Coating aggregate with SCA.

Adding SCA to the monomer produced no increase in strength of the PC. Coating aggregate with SCA will be discussed in subsection 2.6.2.2.

The use of water soluble epoxies was attempted. Epi-Rez®, manufactured by Celanese Polymer Products Company, was selected for use since it is compatible with water. Table 21 summarizes the four monomer formulations used. Formulations A and C involved premixing the Epi-Rez® and Epi-Cure® separately from the

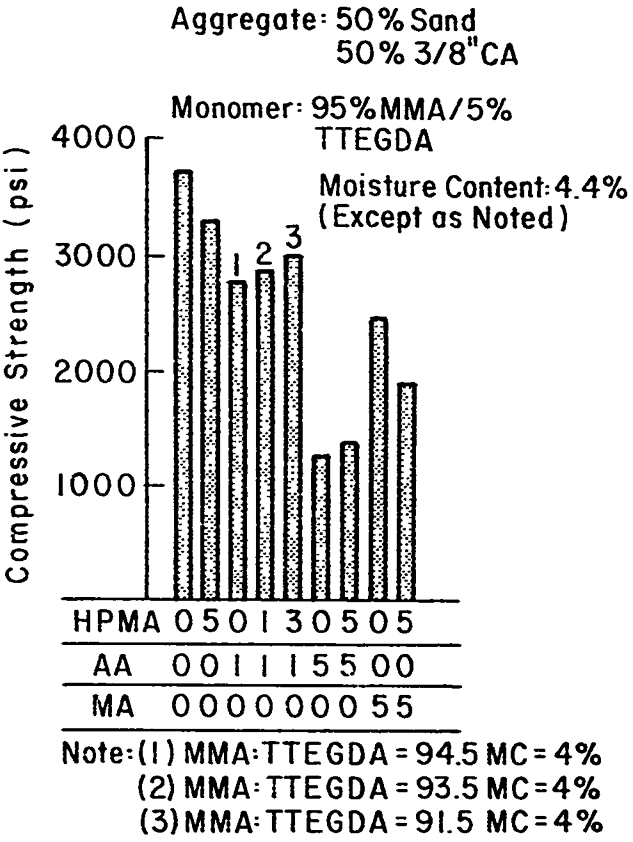


Fig. 40. Effect of Additives on Compressive Strength of PC Made with Wet Aggregate

TABLE 21. USE OF WATER-SOLUBLE EPOXIES AS ADDITIVES TO MONOMER

Formulation	Chemical		Percent by Weight
A	Mixed separately	Epi-Rez 50821	39.70
		Epi-Cure 872	10.30
	Mixed separately	MMA	46.55
		TTEGDA	2.45
		BzP	0.65
		DMPT	0.35
B		Epi-Rez 50821	49.00
		MMA	46.55
		TTEGDA	2.45
		BzP	1.30
		DMPT	6.70
C	Mixed separately	Epi-Rez 5046	4[illegible].25
		Epi-Cure 828	6.75
	Mixed separately	MMA	46.55
		TTEGDA	2.45
		BzP	0.65
		DMPT	0.35
D		Epi-Rez 5046	49.00
		MMA	46.55
		TTEGDA	2.45
		BzP	1.30
		DMPT	0.70

MMA/TTEGDA system and then mixing the two materials together. None of the formulations was successful. The PC did not cure, and the mixed material was too viscous to mix properly with the aggregate.

2.6.2 Aggregate Treatment

2.6.2.1 Moisture Absorptive Additives. Four moisture absorptive additives were investigated: portland cement (Type 3), lime, gypsum, and Type J cement. Cement (or lime) was added to the wet aggregate just prior to adding monomer. The 3-inch x 6-inch cylinder specimens were tested for compression strength and splitting tension strength three days after casting. For a moisture content of 5.9 percent and 3 day cure time, 6 percent of cement produced a 113 percent increase in compressive strength and a 95 percent increase in splitting tensile strength compared to specimens in which no cement was used. Nine percent cement resulted in a 115 percent increase in compressive strength and a 120 percent increase in splitting tensile strength. Tests were then performed on specimens made 3 hours after casting. The results for splitting tensile strength are compared for 3 days and 3 hours cure time in Figure 41. The 3 hour cure times produced only slight increases for the cement specimens and a reduction in strength for lime.

Type J cement, a special cement designed for curing at high temperatures in oil well applications, was used in some tests.

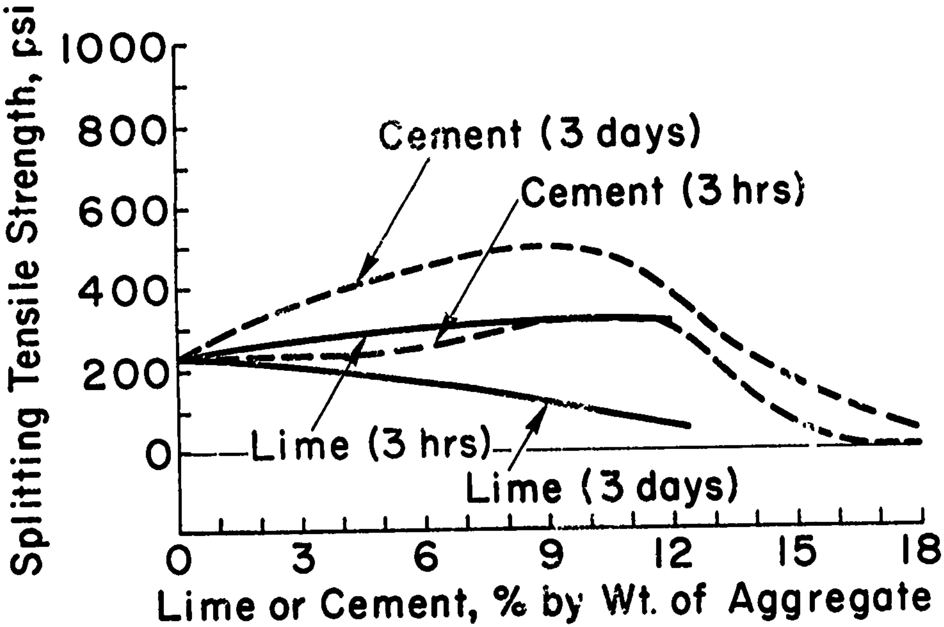


Fig. 41 Effect of Lime and Type : Cement on Splitting Tensile Strength of PC Made with Wet Aggregate (MC = 5.9%)

Type J cement has a high dicalcium silicate content, which is compatible with MMA. Figure 42 shows the results for splitting tensile strength of specimens made with 4.5 percent and 7.67 percent moisture content and tested after 3 day and 3 hour cure times. It was noteworthy that, even at 7.67 percent moisture, J cement resulted in strengths greater than 300 psi. For 4.5 percent moisture contents, however, a reduction in strength occurred.

The use of two kinds of gypsum was evaluated since it gains strength very quickly when mixed with water. However, no strength gain was obtained for either 3 or 6 percent of gypsum. The use of lime and cement additives does not appear to provide a solution for wet aggregate.

2.6.2.2 Coated Aggregate. It was theorized that the use of aggregate coatings could be useful for producing PC when moisture is present. The coated aggregate would provide a better surface for bonding to the polymer in addition to preventing moisture from being absorbed into the aggregate.

The first coating investigated was poly methyl methacrylate (PMMA). The formulation used was 70 percent MMA, 30 percent MMA syrup (a partially polymerized MMA monomer which has a viscosity of 500 centipoise), 2 percent BzP, and 1 percent DMPT. The 3/8-inch silicious limestone aggregate was then placed in the oven at 220^{O}F to accelerate polymerization. The aggregate was frequently stirred to prevent adhesion. Polymerization required 40 to 60 minutes.

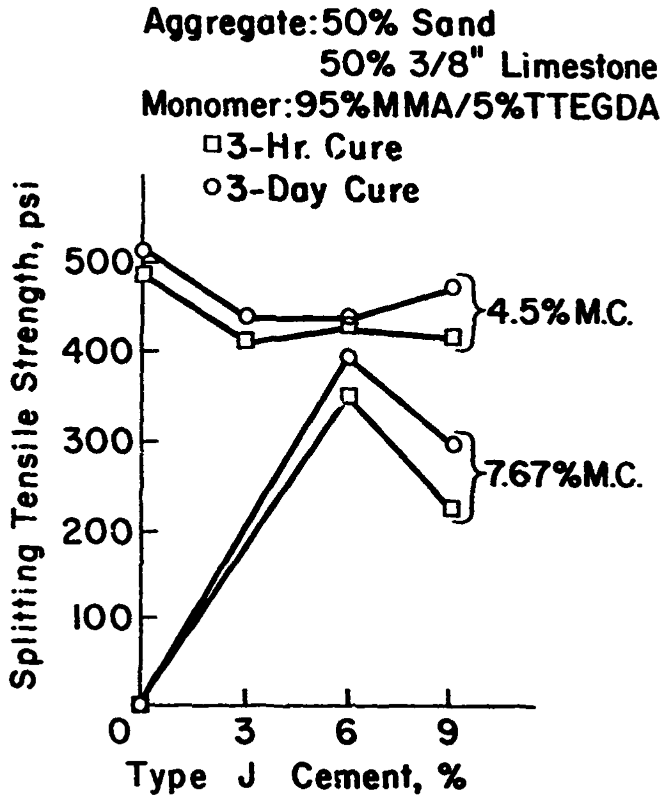


Fig. 42. Effect of J Cement on Splitting Tensile Strength of PC Made with Wet Aggregate

The coated aggregate was soaked in water for 24 hours before monomer was added to make polymer concrete cylinders. Coated and uncoated coarse aggregates were used to provide a comparison. Figure 43 gives the splitting tensile strength for the specimens. The polymer coating provided no increase in strength; in fact, lower strengths were obtained. Apparently the polymer coating prevented most of the water from entering the aggregate, resulting in more free water to produce a lower quality PC.

The second coating investigated was silane coupling agent (SCA) (Union Carbide A-174). Diluted acetic acid was added to distilled water to give a pH of 4.5 to 5. Five volume percent SCA was added to the water. The dry aggregate (equal weights of sand and 3/8-inch coarse aggregate) were soaked in the solution for either 10 minutes or one hour. The aggregate was drained and cured in the oven at 120°F over night. After cooling, the aggregate was soaked in water for at least 24 hours before making 3-inch x 6-inch PC cylinders.

The compressive and splitting tensile strengths are given in Table 22 and shown in Figures 44 and 45, respectively. While some reduction in compressive strength occurred for PC made with coated aggregate with increasing moisture content, the compressive strength was 5290 psi for 4.3 percent moisture. Tensile strength was 870 psi for the same condition, but there was little reduction in strength from the specimens with 1.1

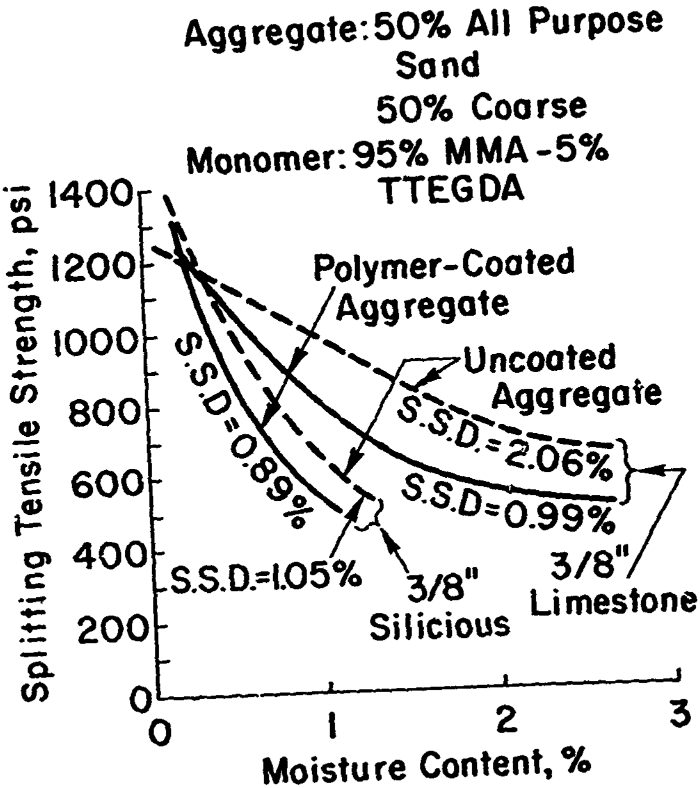


Fig. 43 Effect of Polymer Coated-Aggregate on Splitting Tensile Strength of PC Made with Various Moisture Contents

TABLE 22. EFFECT OF SILANE COUPLING AGENT COATED AGGREGATE ON STRENGTH[b]

Coarse Aggregate[a]	Moisture Content, %	Soaking Time, min.	Compressive Strength, psi			Splitting Tensile Strength, psi		
			Coated Aggregate		Non-Coated Aggregate	Coated Aggregate		Non-Coated Aggregate
Silicious	1.3	10	6340 5740 6200	Avg. 6090	4050[c]	900 910 890	Avg. 900	620[c]
	2.8	10	4020 3750 3890	Avg. 3890	2700[c]	670 640 660	Avg. 660	400[c]
	1.1	60	6960 6790 7530	Avg. 7100	4350[c]	940 920 850 840	Avg. 890	680[c]
	2.1	60	6340 6930 6870	Avg. 6710	3200[c]	940 970 900	Avg. 940	470[c]
	4.3	60	5020 5520 5260	Avg. 5290	2050[d]	880 840 890	Avg. 870	340[d]
Limestone	2.5	60	6110 6290 5930	Avg. 6110	4550[d]	880 810 870	Avg. 850	670[d]

[a]Fine aggregate: all-purpose sand
Coarse aggregate: 3/8-inch silicious or limestone

[b]Monomer: 95% MMA; 5% TTEGDA

[c]Interpolated value

[d]Extrapolated value

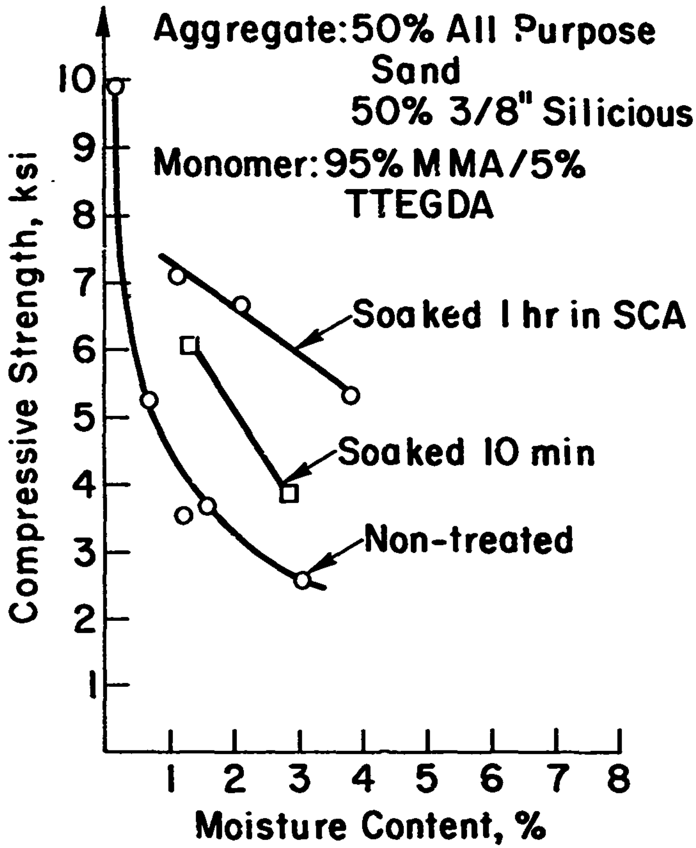


Fig. 44. Effect of Silane Coupling Agent-Coated Aggregate on Compressive Strength of PC Made with Wet Aggregate

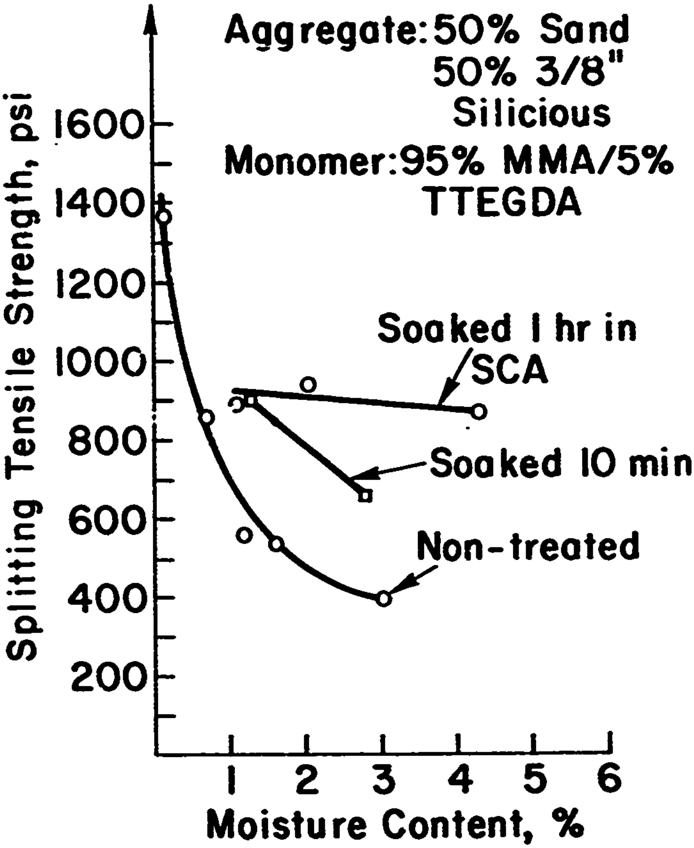


Fig. 45 Effect of Silane Coupling Agent-Coated Aggregate on Splitting Tensile Strength of PC Made with Wet Aggregate

percent moisture content. It is apparent that the longer soaking time in SCA is important since the strengths for one hour soaking were considerably greater than for 10 minutes. The use of SCA-coated aggregates appears very promising if the process for coating aggregates on a large scale can be perfected.

2.6.2 Addition of Fibers. The use of fibers in the PC mix was investigated to improve the strength when moisture is present. Fibers are available in glass, polymer, and steel, and steel fibers are available in several types and sizes.

A screening study was conducted to evaluate the fibers in PC. The PC was made using a monomer formulation of 95 percent MMA and 5 percent TTEGDA. The aggregate consisted of 50 percent all-purpose sand and 50 percent 3/8-inch crushed limestone aggregate. Both 3-inch x 6-inch and 6-inch x 12-inch cylinders were made. Fibers used were steel (Bekaert), alkaline-resistant (AR) glass, polyethylene, and polypropylene. Percentages of fibers by weight of aggregate varied. Results are given in Table 23.

Based on the initial tests, the ZL 30/50 fibers, which had the highest strength of 1838 psi, were selected for further use in PC made with wet aggregate. The aggregate, which consisted of 50 percent all-purpose sand and 50 percent 3/8-inch crushed limestone, was first dried at 250°F, cooled to room temperature, wetted to provide the desired moisture content, and permitted

TABLE 23. SPLITTING TENSILE STRENGTH OF PC MADE WITH DIFFERENT TYPES OF FIBERS[a]

Fibers Type	Percent, Weight	Splitting Tensile Strength, psi	Cylinder Size, inch	Percent, Increase[b]
None	0.0	1260	3 x 6	--
None	0.0	1040	6 x 12	--
AR GLASS 1 inch	0.96	1302	3 x 6	3.3
AR GLASS 1 inch	1.60	1315	3 x 6	4.4
AR GLASS 1 inch	2.24	1375	3 x 6	9.1
POLYETHYLENE (short)	0.58	490	3 x 6	—
POLYPROPLYNE	0.60	614	3 x 6	—
STEEL 0.4mm x 30mm	2.0	1355	3 x 6	7.5
STEEL 0.4mm x 30mm	2.5	1385	3 x 6	9.9
STEEL 0.4mm x 30mm	5.0	1735	3 x 6	37.7
STEEL 0.4mm x 30mm	7.0	1690	3 x 6	34.1
STEEL 0.5mm x 50mm	5.0	1750	3 x 6	38.9
STEEL 0.5mm x 50mm	5.0	1425	6 x 12	37.0
STEEL (Galvanized) 0.5mm x 50mm	5.0	1195	6 x 12	14.9
STEEL 0.5mm x 30mm	5.0	1838	3 x 6	45.9

[a]95% MMA; 5% TTEGDA
Moisture Content = 0%

[b]3x6 control cylinder strengths were used as references for 3x6 PC specimens; 6x12 control strengths used as reference for 612 PC specimens

to soak for at least 24 hours. The steel fibers were added as a percentage of the dry aggregate weight and thoroughly mixed. The monomer (95 percent MMA and 5 percent TTEGDA) was added and mixed into the aggregate. The PC specimens were then cast into molds.

Compressive strength is shown in Figure 46 for PC (3-inch x 6-inch cylinders) made with a moisture content of 3.7 percent. For 5 and 7 percent fibers, significant strength increases resulted. Splitting tensile strength is shown in Figure 47 for 3.7 percent moisture. One data point is shown for 5 percent fibers and 5 percent moisture, which indicates that strength is increased more than 100 percent for 5 and 7 percent fibers for 3.7 percent moisture and by nearly 50 percent for 5 percent moisture. Figure 48 shows a comparison in strength with and without fibers for 3.7 percent moisture for splitting tensile and compressive strength and 5 percent for modulus of rupture.

The use of Type 3 cement with fibers was investigated. Figure 49 indicates the percent increase in splitting tensile strength 4 hours after casting for 3 to 12 percent cement. Five percent fibers and 5 percent moisture content were used in making the PC.

A series of tests was performed using SCA on PC made with 5 percent fibers and 5 percent moisture content. Compared to strength without the use of SCA, the following increases in strength were obtained:

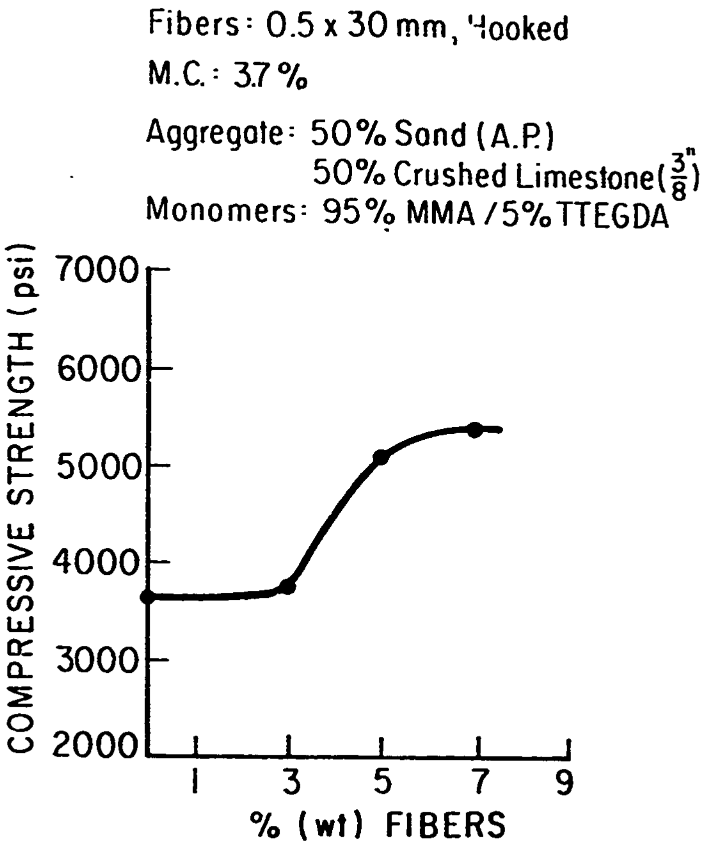


Fig. 46. Fffect of Steel Fibers on Compressive Strength of PC Made With Wet Aggregate

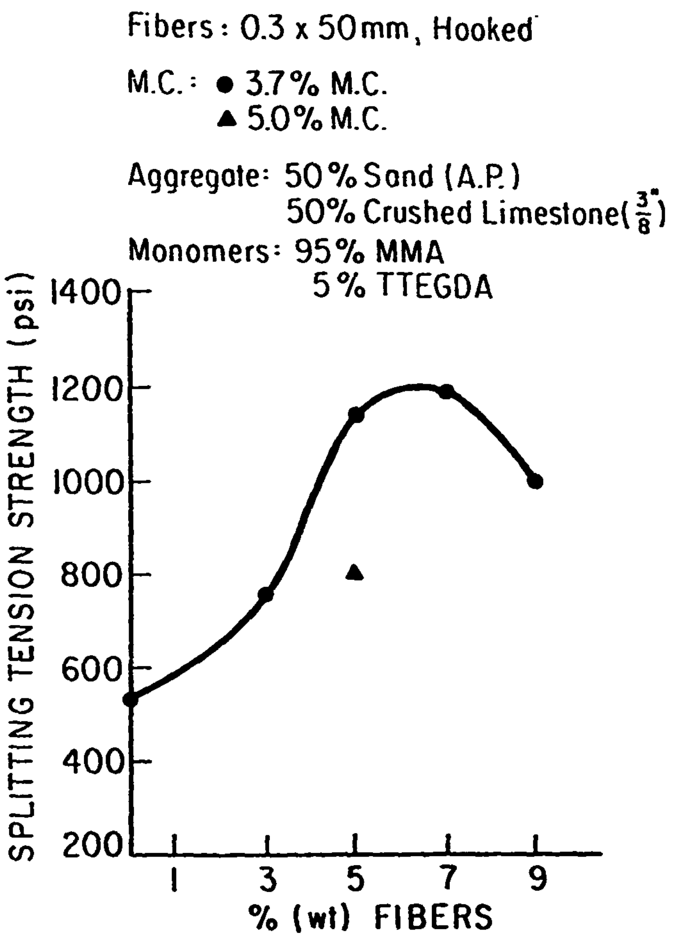


Fig. 47. Effect of Steel Fibers on Splitting Tensile Strength of PC Made With Wet Aggregate

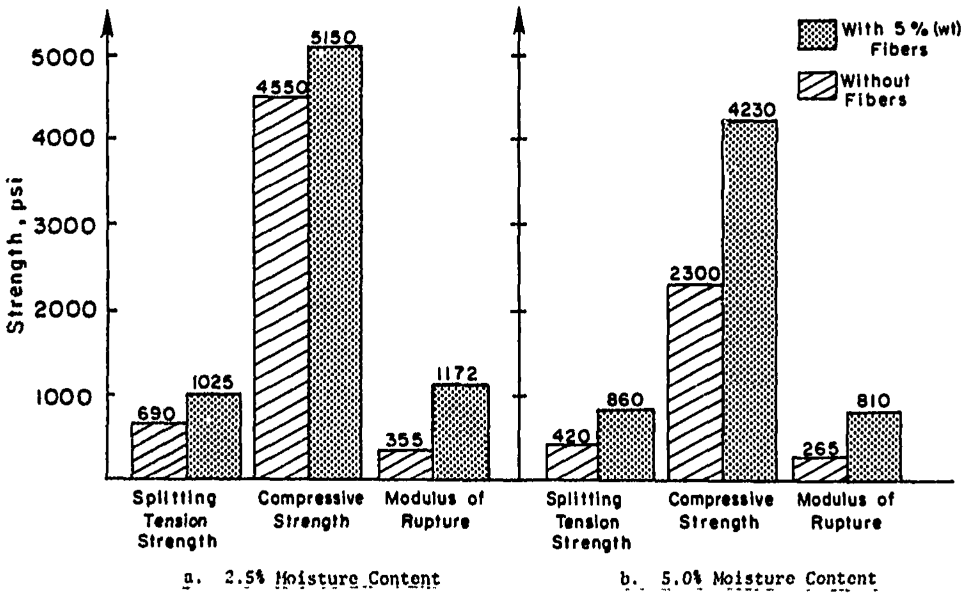


Fig. 48. Comparison of Strengths of PC Made with and without Steel Fibers and with Two Moisture Contents

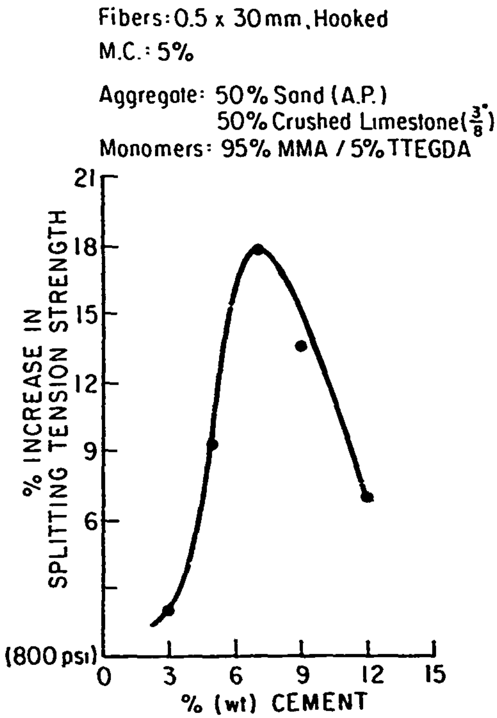


Fig. 49. Effect of Cement Used With Steel Fibers on Splitting Tensile Strength of PC Made With Wet Aggregate

SCA-treated aggregate, 12.5 percent; SCA-treated fibers, 14.25 percent; and SCA-treated fibers and aggregate, 27.0 percent. Using SCA-treated fibers and aggregate, an increase of 48.1 percent in modulus of rupture was obtained for 3-inch x 3-inch x 12-inch beams with a 9-inch span with a 5 percent moisture content and 5 percent fibers compared to a beam with no SCA and with no fibers. An increase of 18.1 percent was obtained for non-treated aggregates and fibers.

The use of steel fibers appears highly promising to minimize the effect of wet aggregate. Fiber-reinforced PC also has the added advantage of producing flexural members with considerable more toughness as evidenced by the load-deflection response shown in Figure 50 for a 3-inch x 3-inch x 12-inch beam with 5 percent fibers and no moisture. The greater toughness and ductility has great potential for insuring longer life for bomb damage repair applications.

2.7 Effect of Asphalt on PC

In many bomb-damaged runway repairs, the polymer concrete will be in direct contact with surrounding asphalt overlays. In some repairs, the spall will not extend through the asphalt; in others, the repair will extend through the asphalt and into or through the concrete.

It has been found that the monomer acts as a solvent on the asphalt and that the presence of asphalt serves to inhibit polymerization. Studies were conducted to determine the effect

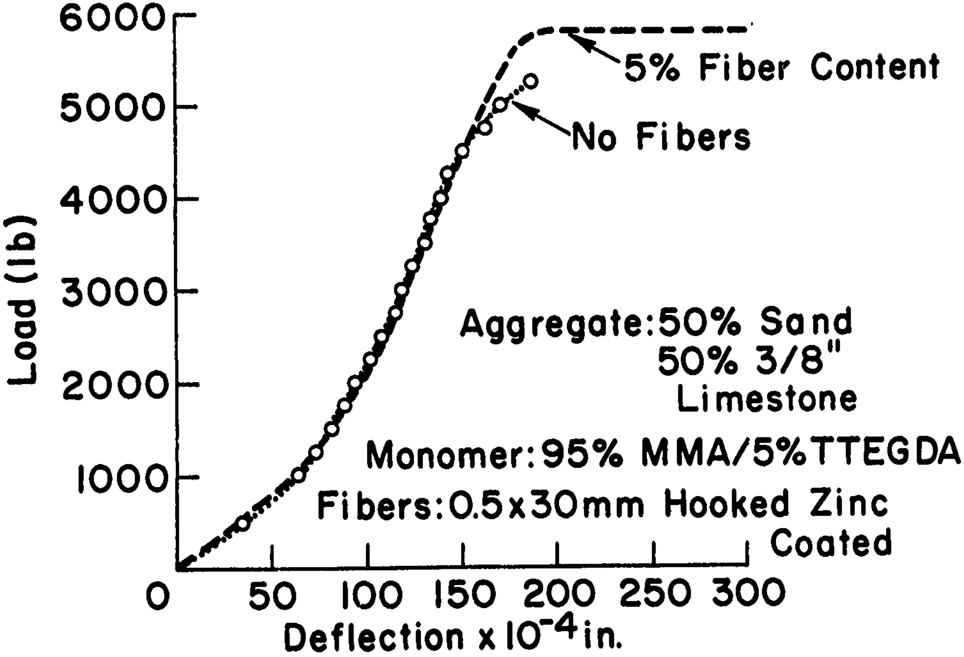


Fig. 50. Load-Deflection Response of PC Beams Made with and without Steel Fibers

of asphalt on the curing time and strength of the polymer concrete.

Preliminary tests were performed by testing asphaltic concrete cores in splitting tension, and bonding the two halves together with polymer concrete and retesting the specimen to determine splitting tensile strength. However, the surface-to-volume ratio of the PC was so large that the inhibiting effect of the asphalt required several hours for polymerization. It was determined that another test, preferably to measure shear, would be preferable.

The next tests were conducted by coring a 1-1/8-inch diameter hole through the center of a 2-inch x 4-inch HVEEM stabilometer specimen made with Type AC 20 asphaltic concrete provided by the Texas State Department of Highways and Public Transportation. The hole was then filled with PC. After peak exotherm had occurred, the PC cylinders were punched out of the HVEEM stabilometer specimens by use of a hydraulic testing machine, and the shear strength was calculated.

It was noted when coring the HVEEM stabilometer specimens that different percentages of aggregate were exposed. Although all specimens were Type AC 20 asphaltic concrete, the difference in percentages of aggregate was accounted for by the fact that the specimens were supplied from several highway construction sites across the state. As a result, there were inconsistencies in the gradation due to the variation in quantity and size of aggregate used. To account for this varying gradation, all samples were segregated into three groups by visual inspection of the approximate percentage of exposed aggregate at the interface of the cored specimen.

Upon testing it was discovered that as the percentage of exposed aggregate increased there was a corresponding increase in punching shear stress. This was due primarily to the mechanical bonding developed between the monomer and the aggregate.

The punching shear tests were abandoned for several reasons. The smooth surface at the interface resulting from coring did not accurately simulate the actual rough interface that would result from blast effects. This resulted in unrealistically low values of ultimate shear stress. An attempt was made to roughen the surface of the surface area by brushing it with a wire brush; however, this did not alter the fact that the surface of the exposed aggregate was cut smooth. Another potential solution was to drill through the specimen rather than core it, but two problems arose. First, it was extremely difficult to anchor the specimen properly to resist the vibration induced by the drill when it came into contact with the aggregate. The second problem was more severe in that, when the drill came into contact with the aggregate, it literally ripped the aggregate out of the asphaltic concrete rather than cutting it, which would have resulted in very inconsistent data when shear tests were performed.

A pull-out test was developed to measure the bond stress. To achieve more consistent results in the test data, asphaltic concrete specimens were made in the laboratory using the criteria for mix design specified by the Federal Aviation Administration (FAA). Each HVEEM stabilometer specimen was cast with a 2-inch diameter by 1-inch long steel plug at its center. Upon removal of the plug the specimen was cooled in a freezer for 5 minutes at $-30^{\circ}F$ to harden the asphalt and the hole was brushed with a wire brush to expose the aggregate. A thin disk of aluminum foil was then placed in the bottom of the hole to eliminate any tensile forces generated during pull out of the PC plug. The hole was then filled with PC, and a steel U-bolt was embedded as an attachment point for the testing machine (Figure 51). Three PC formulations utilized in this test procedure are given in Table 24.

When preparing the PC formulations using the monomer (MMA), the hole in the HVEEM stabilometer specimen was filled with sand, and the monomer was poured over it until saturation occurred. A thermocouple was inserted at the interface to measure peak exotherm. Due to the small volume of the hole, coarse aggregate was not used.

In the first batch of specimens the mix design of the asphaltic concrete was varied to determine which mix gave the optimum bond strength. The FAA has stipulated a specific mix design for runways subjected to heavy aircraft. This design is based

TABLE 24. ASPHALT PROPERTIES AND PC FORMULATIONS

Asphaltic Concrete

Asphalt
Type - AC 20
Penetration at 77°F - 64
Specific Gravity at 77°F - 1.003

Aggregate: Crushed Limestone

Aggregate Gradation

	Percent by Weight Retained		
Sieve Size	Type D	Type DC	Type C
5/8"			5
3/8"	5	5	40
#4	35	50	20
#10	25	20	10
#40	10	10	10
#80	10	5	5
+200	10	5	5
-200	5	5	5

Polymer Concrete Formulations

Silikal®
Powder - 87.3%
BzP - 1.5%
Liquid - 11.2%

95% MMA/5% TTEGDA
BzP - 3.125%
DMPT - 6.25%
Aggregate: all-purpose sand

95% MMA/5% TMPTMA
BzP - 3.125%
DMPT - 0.625%
Aggregate: all-purpose sand

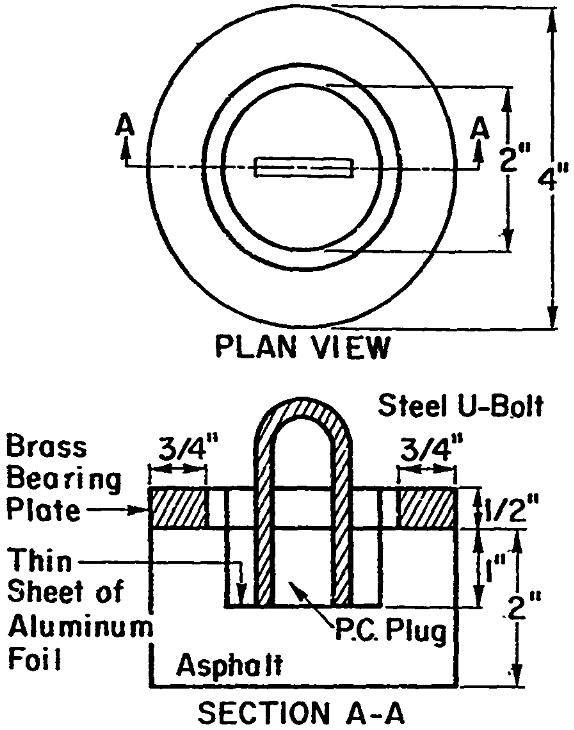


Fig. 51. Typical Specimen for Pull-Out Test

on ASTM D3515 and ranges from Type 4A to 6A. It was decided to use the Texas State Department of Highways and Public Transportation specifications (Reference 6) that correlate to the ASTM standards. These are:

D - Fine Surface Course.

DC - A Coarser Gradation of Type D.

C - Coarse Surface Course.

Asphalt Content Percent by Total Weight of Mix, 4 to 8.

Asphalt Type AC 20 Penetration, 60 to 70.

The three gradations are illustrated in Table 24.

From the results in Figure 52, the optimum bond strength was achieved by using a Type C mix with 6 percent asphalt content. Although the Type D mix with 7 percent asphalt content gave a higher ultimate shear stress, the stability associated with this mix is equal to seventeen, which is less than the minimum of forty required by the FAA.

The upper curves in the graph are for asphaltic concrete without the PC added. These shear strengths were found by punching out the asphaltic concrete below the void in the HVEEM stabilometer specimen (Figure 51).

From the graph, the PC formulation utilizing TTEGDA performed poorly when compared to the Silikal®. Upon examination of the test specimens, it was discovered that the monomer along the interface had not polymerized sufficiently to allow good

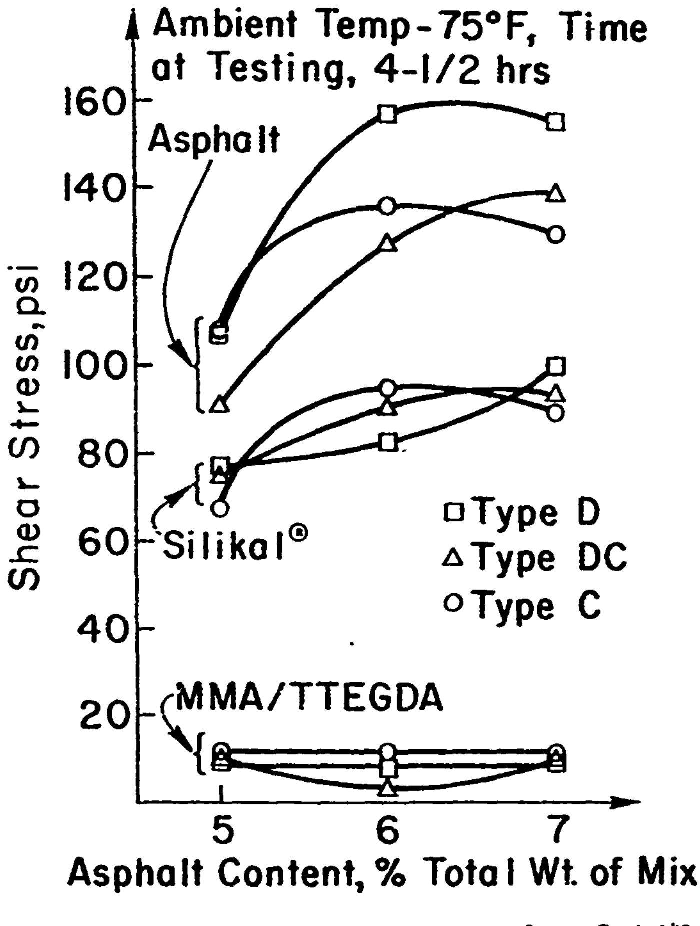


Fig. 52. Shear Strength for Asphalt to Polymer Concrete Interfaces for Various Types of Asphalt

bond to develop. This was apparently due to the solvent action of the monomer on the asphalt. As the asphalt approached a liquid state, the asphaltic concrete (AC) matrix was weakened, which, in turn, led to low bond stress. Additionally, due to the low viscosity of the monomer, the weakened AC matrix enabled the monomer to penetrate further into the specimen, perpetuating the problem and resulting in low concentrations of monomer in the repair area. This action resulted in extending the polymerization rate and leaving pockets of unpolymerized material.

Silikal® performed much better due to the fact that its mixture had a much higher viscosity than the MMA mixture. Consequently, the Silikal® polymerization rate was rapid (14 minutes), which left an insufficient amount of time for the solvent action of the monomer to damage the AC matrix, resulting in a much higher bond stress. This was made evident by significant shearing of the aggregate at the interface and some adhesion of the asphalt to the plug during pull-out.

To improve the performance of the TTEGDA formulation, the interface of the hole in the specimen was coated with a high viscosity primer made of MMA. This resulted in a 273 percent increase in strength, and the polymerization rate was also increased (Figure 52).

A PC formulation utilizing TMPTMA in lieu of TTEGDA exhibited much lower polymerization rates. When used with the primer, there was a 44 percent increase in strength over the TTEGDA formulation with primer (Figure 53).

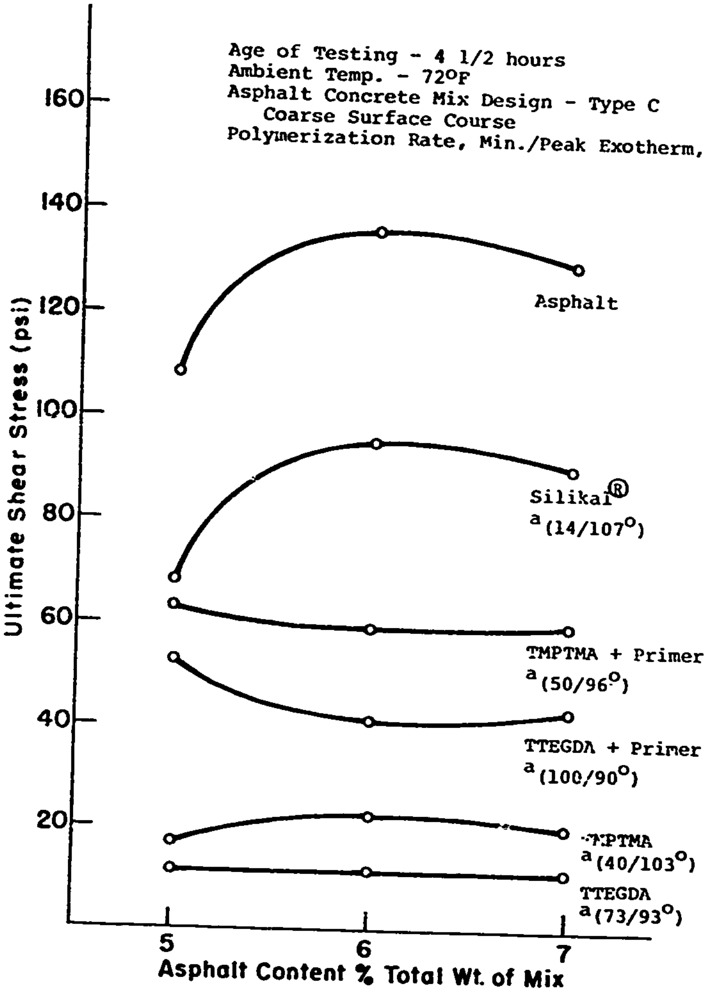


Fig. 53. Shear Strength for Asphalt to Polymer Concrete Interfaces

Although the primer did improve the bond strength of the TTEGDA and TMPTMA formulations, their performance still falls considerably short of that using Silikal®. Other potential solutions to further improve bond strength involve the addition of powdered PMMA, use of MMA syrup, or increasing the concentration of the initiator and promoter. All of the above solutions would tend to increase the viscosity of the monomer formulation and reduce its polymerization rate. These variables will be incorporated into the next phase of testing, which will include the investigation of bond strength under various ambient temperatures.

The results of tests performed to date and of previous tests performed in the field in which MMA came into contact with asphalt indicates that no significant problem should be expected in making MMA PC repairs on runways with asphalt overlays.

SECTION III

PRELIMINARY REPAIR PROCEDURES

3.0 Introduction

In this section two preliminary methods of repair are presented. Two facets of the construction were given particular consideration. One was to select a repair procedure that would minimize personnel requirements. The second was to select a repair procedure that would use the types of equipment existing at most bases.

3.1 Types of Runway Damage

Four types of bomb damage were considered in this investigation: (1) surface spalls of concrete which do not extend full depth and which have diameters less than 5 feet; (2) small craters, with diameters less than 20 feet and depths of 1 to 5 feet; (3) large craters, with diameters up to 70 feet and depths of 5 to 15 feet; and (4) camouflet, bulb-shaped craters caused by runway piercing weapons in which a small diameter hole is produced in the concrete and a larger crater is produced beneath the surface. With regard to camouflet, it is assumed that when the upheaved surface is removed, the crater will be similar to type (2) except that the debris will be contained within the crater. Hence, the repair technique will not be significantly different from that proposed for craters of type (2).

3.2 Repair Considerations

For each repair considered, it is assumed that the upheaved surface will be removed and, for the most part, a clean crater will be what remains to be filled. Obviously, if the repair procedure requires a partial debris fill, the debris should not be removed from the crater but left in place, with additional fill material added to bring the surface to grade.

Many of the existing runways have a portland cement concrete (PCC) pavement overlaid with an asphaltic concrete (AC). Laboratory results and field tests have shown that the asphalt does not significantly affect the repair. Hence, the repair techniques presented will not differentiate between PCC pavement with and without overlays. The term "surface" shall refer to the existing surface, either PCC or AC. The term "existing pavement" shall refer to whatever exists above the base material. The term "debris" is assumed to include PCC, AC, base material, and subgrade material, if the subgrade is penetrated by the crater.

Two methods of producing polymer concrete (PC) are being investigated. One is the preplaced aggregate method which has been successfully used by the research team in numerous pavement and bridge repairs. Aggregate is placed to surface grade, and the monomer system is applied in one of several ways. It can be premixed and poured or sprayed over the aggregate until the aggregate is saturated, or the initiator can be mixed in-line at the nozzle of an application gun as the monomer is applied. The gun nozzle can be placed into the aggregate to minimize entrapped air in the PC. The advantages of the preplaced aggregate with the user-formulated monomer systems are (1) elimination of separate mixing operations and (2) significantly reduced cost for the monomer system.

Another method is the premixed system. In this method the aggregate and chemical components are premixed in a mixer prior to placement. User-formulated monomer systems can be used for this method, but the commercially available prepackaged systems are more commonly used. The powder and liquid components are mixed with aggregate in a mixer and placed similarly to PCC. Admixtures in the prepackaged system provide workability characteristics similar to PCC. These materials generally develop a skin on the surface of the repair within a short time of placement that minimizes evaporation and the danger of combustion. The advantages of the prepackaged system are (1) workability characteristics, (2) reduced shrinkage, and (3) ability to form a surface skin.

Both methods will be investigated in Phase II since both methods provide considerable potential.

3.3 Spall Repairs

Field tests by both the Air Force and the research team have shown that spalls can be adequately repaired by either filling the spall with PC or using fill material to within a inches of the surface and then capping the repair with 8 inches of PC. Figure 54 illustrates a typical repair cross section. Figures 55 and 56 illustrate typical spall repairs. The spalls shown were made with debris as the aggregates with sand added at the surface for finishing purposes.

Debris may be used for all or part of the aggregate required in the surface layer provided it does not contain asphalt and the gradation permits the repair surface to be finished. Generally, this requires 3/4-inch aggregate or less. If the aggregate is larger, sand must be added in order to provide a reasonable riding surface.

Debris may be used for the fill material if the spall is deep enough to require fill. When fill is required, care should be exercised to avoid large void areas and to compact the fill enough to support rubber-tired vehicles, such as a truck or front-end loader.

As a part of this project, an in-line mixing system has been developed for use in the preplaced aggregate method. The in-line mixing system minimizes the need for premixing chemicals and allows the chemical proportions to be adjusted at the time of placement. For example, the time of set can be varied to satisfy construction conditions, such as temperature or placement requirements. The prototype is shown in Figure 57. Figure 58 shows the unit in a field test of spall repair at Tyndall Air Force Base.

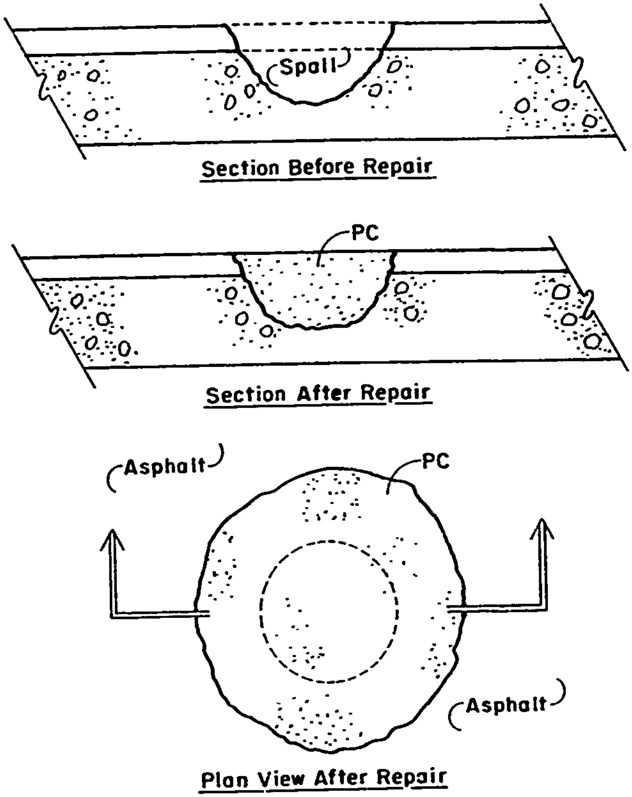


Fig. 54. Typical Spall Repair

Fig. 55. Field Test of Spall Repair Using Debris Aggregate

Fig. 56. Debris Spall Repair after Traffic

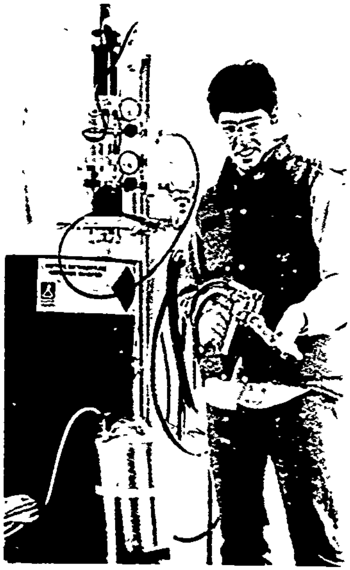


Fig. 57. Prototype In-Line Mixing Unit

Fig. 58. Spall Repair Field Test

3.4 Small Crater Repair

3.4.1 Cap Method. Small craters can be effectively repaired with the cap method, as illustrated in Figure 59. The cap method is outlined in the steps that follow:

(1) Fill the crater to within 10 to 14 inches of the surface with debris or select fill. The debris should be compacted with a vibratory roller.

(2) Place a levelling course of select material. The material may be sand or gravel. This layer need not be compacted, and its moisture is not critical.

(3) Using the in-line mixing gun, prime and seal the levelling course and the perimeter of the repair faces with a fast-setting monomer.

(4) Place a well-graded aggregate mix to surface grade. A front-end loader should be acceptable for placement and initial screeding of the surface.

(5) Inject monomer into the aggregate, using one or more in-line mixing units, until the aggregate is saturated.

(6) Add sand where required to match surface grade.

(7) Finish with hand-held float.

As an alternate to using the preplaced aggregate method, using premixed PC will be considered. Steps 1 and 2 would be the same as for the first method. The additional steps required are:

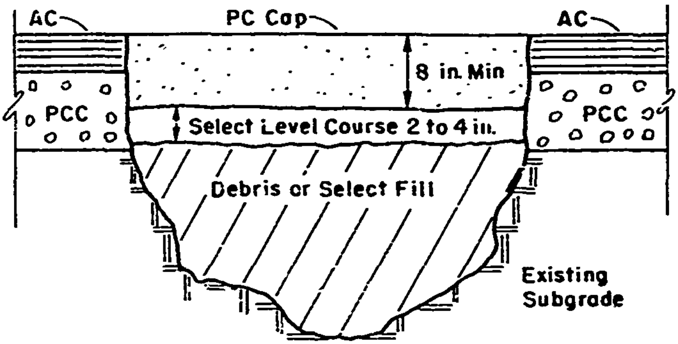


Fig. 59. Typical Cross-Section of Small Crater Repair - Cap Method

(1) Mix the prepackaged PC system components with additional aggregate added in one or more Concrete-Mobiles®.

(2) Place the PC in the repair area and screed the surface.

3.4.2 Precast Slab Method. When the condition of the crater requires the removal of one or more existing pavement slabs, use of the precast system of repair should be considered.

The precast unit should be sized to match existing pavements. For example, if the existing joints are 15 feet apart, each precast unit should be 7 feet by 7 feet. Four units would be required to replace one existing slab, and the joint of 4 to 6 inches between the slabs would be filled with PC, using either the preplaced aggregate or the premixed methods. A typical precast unit is illustrated in Figure 60. The keyway shown on all edge faces provides for load transfer independent of bonding. The lift or drag keys are placed to permit the unit to be lifted or dragged into place. There are several commercially available lift or drag pins. The one selected should have be detachable parts.

When the precast system is used, the existing pavement should be removed as complete slabs where possible. This will provide rectangular repair areas, which will facilitate the use of the precast units. See Figures 61 and 62 for typical repair configurations.

The precast units can be fabricated from either PCC or PC. If PCC is used and the units are placed as the riding surface,

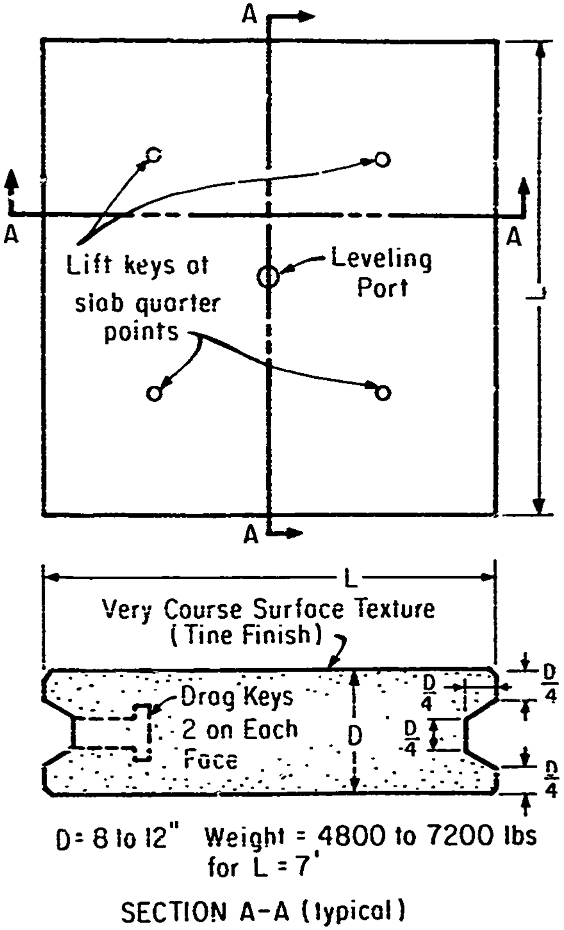


Fig. 60. Precast Slab

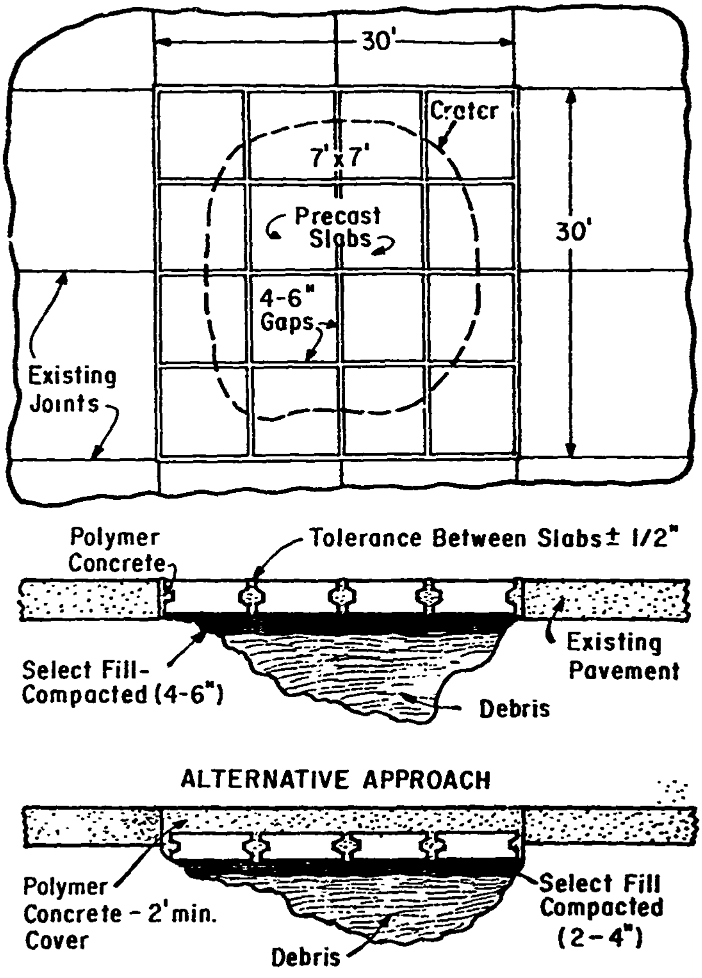


Fig. 61. Repair of 30-Foot Crater - Impact Near Center of Slab

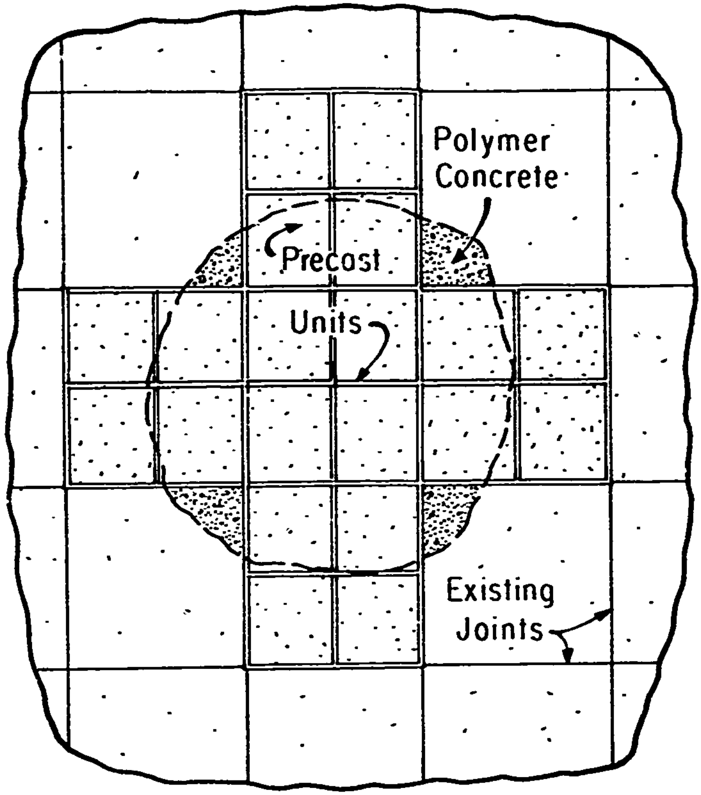


Fig. 62. Repair of 30-Foot Crater - Impact Near Center of Slab

they should be a minimum of 12 inches thick. In all other cases, 8 inches should be considered a minimum thickness. The weight of a unit of PCC 7 feet by 7 feet by 12 inches is about 7300 pounds. This weight is within the lifting capacity of most truck-mounted, telescoping cranes at the distances required.

Two methods utilizing the precast units are proposed, as illustrated in Figure 61. On one method, the top of the unit is flush with the riding surface. This method requires that the units be lifted into place and held at grade until adjustable levelling shoes can be fixed, if necessary. Once the shoes are fixed, polymer is pumped in the joints and/or through the levelling port to fill the void beneath the slab. The void between the slabs is then filled with PC to complete the repair. The alternative method is to drag or lift the precast units into place on the prepared base. PC is placed in the voids between the slabs, and then the entire repair area is covered with PC in a manner similar to the cap described in subsection 3.4.1. In either method the prepared base is the same as described in items (1), (2), and (3) of subsection 3.5.1.

3.5 Large Crater Repairs

The cap method described in subsection 3.4.1 can be used to repair large craters. However, a major difficulty lies in screeding the 8-inch thick PC over the large areas that must be finished. The long screed required would be either too flexible or too heavy for hand use. The use of hand-held floats would require personnel to stand in or on the hardening PC, which would not be desirable from either a safety or a construction standpoint.

The precast systems described in subsection 3.4.2 would be utilized for the large craters. If the PC overlay system is used, the final finishing could be done by hand floating small areas, say 10 feet by 10 feet, before adjacent slabs are covered. Thus, personnel would not be standing in or on hardening PC during the finishing process.

SECTION IV

EXPERIMENTAL BEHAVIOR

4.0 Introduction

Laboratory studies began in Phase I and will continue in Phase II to determine mechanical properties of polymer concrete (PC), including flexural strength, modulus of elasticity, and compressive strength, and to determine fatigue behavior for PC and PC-repaired portland cement concrete (PCC) slabs.

4.1 Mechanical Properties

Mechanical properties have been determined for a wide range of monomer formulations and wet aggregate treatments (Section II). The initial tests were designed to screen the PC for properties to determine the relative strengths. Generally, one or more of the following tests were used: splitting tensile strength (3-inch x 6-inch cylinder); compressive strength (3-inch x 6-inch cylinder); and modulus of rupture or flexural strength (2-inch x 2-inch x 12-inch or 3-inch x 3-inch x 14-inch beams). Splitting tensile tests were frequently used due to the simplicity of casting and testing specimens. These specimen sizes are not as large as required by ASTM standard tests, but the smaller size permitted many more tests to be performed.

Static tests to determine flexural strength (ASTM C78), compressive strength (ASTM C39), and modulus of elasticity (ASTM C39) are nearly completed for the MMA/TTEGDA formulation.

Specimens made at 0°, 75°, and $100^{\circ}F$ will be tested at each temperature, i.e., a specimen cast at $0^{\circ}F$ will be tested 0°, 75^{0}, and $100^{\circ}F$.

4.2 Fatigue Properties of PC Beams

As the static flexural strengths become known, the fatigue strength tests are beginning. Tests are being conducted on 6-inch x 6-inch x 36-inch PC beams using third-point loading with a 30-inch span. Companion 3-inch x 3-inch x 14-inch beams are cast at the same time to provide a measure of the ultimate static strength of the beams.

Beams will be cycled between a maximum stress and a minimum stress which will be greater than zero. The loading will be applied at a frequency of 5 cycles/second until failure or to a maximum of 100,000 cycles. The maximum stress will be held constant for each beam but will be varied from beam to beam to determine the limiting stress. If failure does not occur prior to termination of the cyclic loading, each beam will be subjected to static ultimate load tests. Specimens will be cast at 0°, 75°, and $100^{\circ}F$, and testing will begin two hours after casting.

An initial fatigue test was performed using maximum and minimum stresses of 700 and 175 psi, respectively. The modulus of rupture of the control beam was 1990 psi. The loading was applied for 2,000,000 cycles without any visible cracks occurring. The deflection at the loading corresponding to minimum stress increased from 0.0045 inches to 0.0105 inches during testing, or an increase of 133 percent. For maximum load, the deflection increased from 0.0085 inches to 0.0145 inches, or 71 percent. The static flexural strength at the end of the test was 2580 psi, which was significantly greater than for the control beam. This increased strength may have been due in part to the additional curing that occurred during the five-day testing period.

Subsequent tests are being performed at maximum stresses equal to 60, 70, and 80 percent (and higher if required to produce failure) of the static flexural strength. For this series, the ratio minimum-to-maximum stress of 1:4 will be maintained. Other series will be performed in which this ratio will be varied.

4.3 Fatigue Tests of PC Repairs

A special loading frame was designed to accommodate 3-foot x 6-foot slabs for a maximum load of 100,000 pounds (Figure 63). After adjustments and modifications required to attach the frame to the testing floor and to permit slabs to be installed and removed, tests have begun. Slabs are supported on rubber mats to simulate realistic subgrade stiffnesses.

Several slabs have been tested. The first three tests were not considered successful because of problems with the loading apparatus and because of cracking in the slabs prior to load application. In the last test, two 3-foot x 3-foot x 4-inch

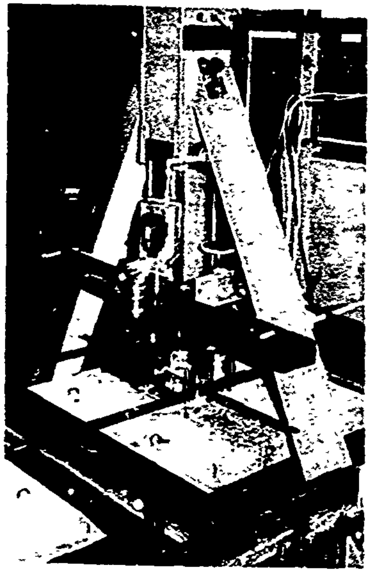


Fig. 63. Fatigue Load Frame

slabs with a keyway edge were joined with PC. The joined slab, designed to test the keyway proposed for the precast system of repair in subsection 3.4.2, was fatigue loaded with a load equivalent to an F-4. Though a crack on one face of the joint appeared early in the test, no loss in load transfer or riding quality (differential movement between slabs) was observed after 10,000 cycles (Figure 64).

Several PC repair configurations have been fabricated for subsequent tests. These were selected to represent critical areas to repair. Figure 65 illustrates some of the configurations to be tested. These slab tests will be concluded in Phase II.

Fig. 64. Keyway Fatigue Test

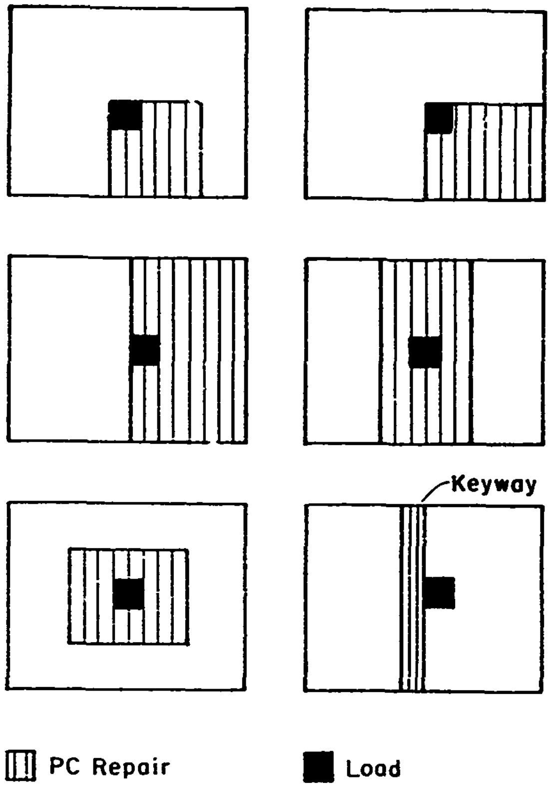


Fig. 65. Typical PC Repair Fatigue Slabs

SECTION V

ANALYTICAL BEHAVIOR OF REPAIRS

5.0 Background

The user must use the material properties, anticipated loading conditions, and desired quality of repair to make a selection of the thickness of polymer concrete to be used in the bomb damaged area being considered for repair. In this section, a procedure is developed to permit the base maintenance personnel to make a determination of thickness for a given location to a minimum time. First, the problem is modeled, and then the more sensitive variables are determined for preparing design charts to predict thickness for a specific condition. This material is then summarized into a design procedure.

5.1 Modeling Runway Repair Area

The objective of this section is to analytically model the behavior of repairs of a portland cement concrete pavement with polymer concrete to develop criteria for the thickness of the repair considering significant variables. In this section, the behavior of repairs is predicted over a practical range of the environmental and loading conditions that are expected at the NATO bases in Europe. This information was supplied by AFESC.

It is essential in any analytical approach that techniques be used to properly model the load, geometry, and material properties to reliably predict the stresses in the pavement. One technique that has been used rather extensively in this study is the SLAB 49 program, developed by Matlock and Hudson and reported in Reference 7.

Figure 66 presents a plan view, and a longitudinal cross section of a runway pavement slab containing a repair area. A typical slab 24 by 36 feet was selected for study. This size has been found to be adequate for studying the stress and deflection distribution for aircraft loadings.

AFESC designated two aircraft types for loading the F-4 and the C-141. These were the primary users of the facilities at the NATO bases in Europe.

For the polymer concrete patches, three sizes were selected: 5 foot x 5 foot, 17 foot x 17 foot, and 24 foot x 36 foot. The thickness of the polymer concrete patch ranged from 5 to 10 inches in 1/2-inch increments. The support values selected were 50, 100, 200, and 300 pounds per cubic inch (pci), with the 50 pci representing a backfill with a minimum compaction.

For the existing portland cement concrete, thicknesses of 8, 12, and 16 inches were considered. The support values selected were 100, 300, and 500 pci. Again, these numbers represented the range of conditions expected at the NATO bases in Europe.

Based on our labor [illegible] and the knowledge of the materials, the followi. parameters were fixed in the study:

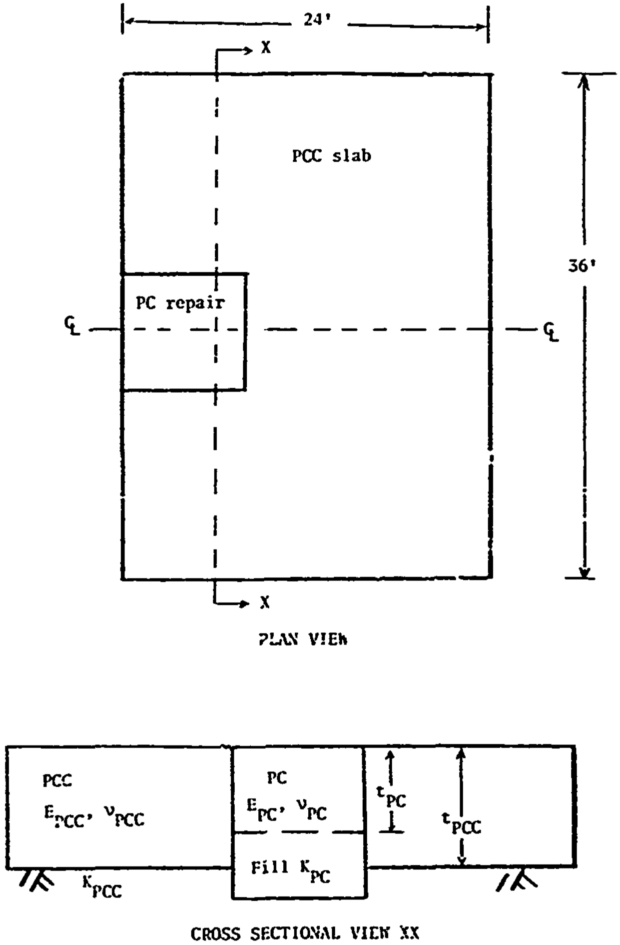


Fig. 66. Runway Repair

$$E_{pc} = 2 \times 10^6 psi$$

$$M_{pc} = 0.30$$

$$E_{pcc} = 4 \times 10^6 psi$$

$$M_{pcc} = 0.15$$

The project contact man directed that the procedures be developed to include the F-4 and C-141 aircraft since these are the primary users of the NATO bases. Figure 67 presents a footprint of the gear configurations of both aircraft. Also shown on the diagram are the weights and the tire pressures selected. Previous investigations have indicated that the stress will vary depending upon the placement of the wheel relative to the edge, corner, and interior conditions. Figure 68 presents the slab loading conditions expected in the field for the various aircraft types and repair conditions. Basically, the conditions range from an interior condition, represented by Position 1, to a corner-edge condition, represented by Position 6. The maximum flexural stress beneath the gear must be determined for all the factors considered to ascertain the critical condition. For the C-141 aircraft, the loads for Positions 1, 2, and 3 were varied slightly as shown in Figure 69, since the tire-gear configuration was tandem. For one placement, the front wheels were placed directly on the repair area centerline, and for the other position, the center of the gear was placed at the center of the patch, as illustrated in the figure.

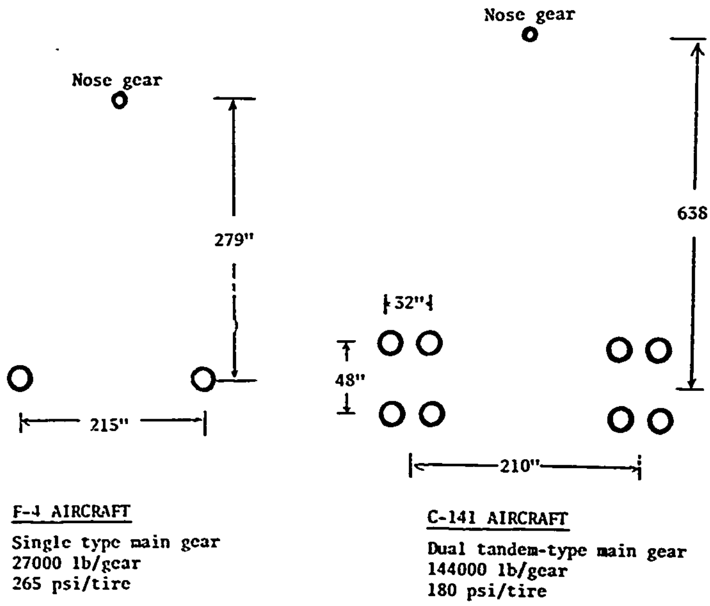
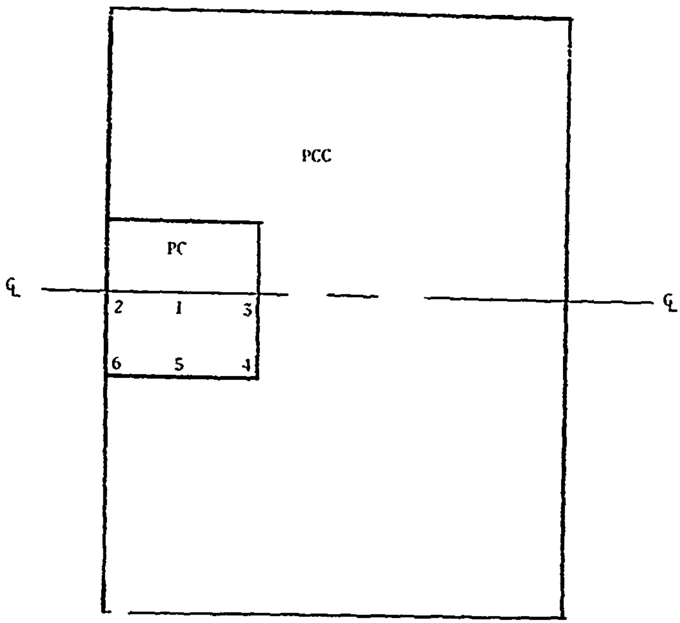
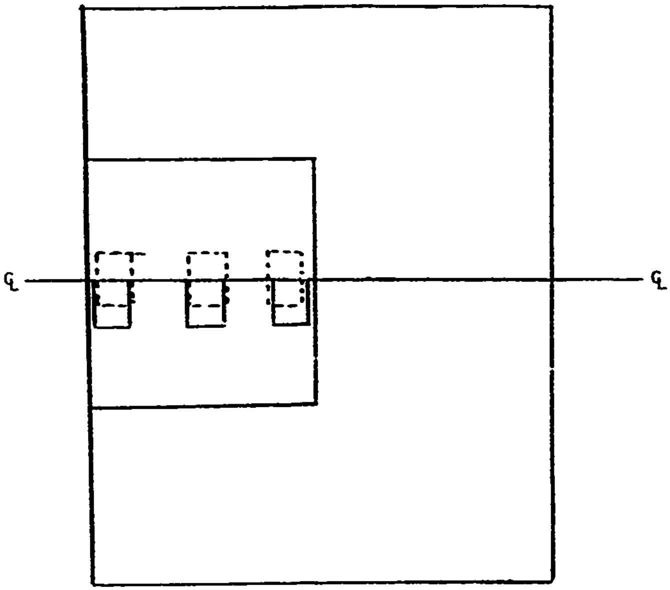


Fig. 67. Aircraft Load and Gear Configurations



Position 1 - Center of patch
Position 2 - Outside Edge
Position 3 - Horizontal PC-PCC interface
Position 4 - Corner PC-PCC interface
Position 5 - Vertical PC-PCC interface
Position 6 - Outside corner

Fig. 68. Horizontal Load Position for F-4 and C-141 Aircraft



Position [solid box] = tires of gear at center of repair

Position [dashed box] = center of gear at center of repair

Fig. 69. C-141 Aircraft Vertical Gear Position

5.2 Sensitivity Study of Variables

In the previous section, a range variable considered in the study was outlined. This presented a large range of conditions for investigation, and as study progressed, it was obvious that some of the variables had low sensitivity and thus had no significant influence on the results. In the following paragraphs, these factors are discussed briefly as to sensitivity to provide background for the reasons some variables are not considered in the analysis.

Relative to the nose gears, the presence or absence of the nose gear did not significantly influence the maximum stress conditions; this may be attributed to the fact that the wheel base distances are 279 and 636 inches for the F-4 and the C-141, respectively. Thus, the nose gear did not have an influence on the results, and for most of the calculations the nose gear was not considered. In addition, the maximum stress was not influenced by the adjacent gear since the wheel tread distances were 210 and 215 inches, respectively. The stresses, reported in subsection 5.3, are the result of studies on one gear and thus would not be different if the entire configuration had been considered.

Considering the horizontal position of the gear, it was found (see Figure 68) that Positions 1, 2, and 3 were critical, while the other positions were less critical, since they received support from the stiffness of the surrounding portland cement concrete. Therefore, the information reported in later sections is relative to Positions 1, 2, and 3.

In the case of the 5 x 5 polymer concrete patch, Positions 1, 2, and 3 are very close to each other, and, subsequently, only Position 2 (edge) was considered, because it is most critical. In the case of the 17 x 17 foot polymer concrete patch and the 24 x 36 foot polymer patch, the study showed that Position 3 has a very low value of flexural stress compared to Positions 1 and 2 for the F-4 aircraft load. Thus, this position was considered to have relatively little influence on the life of the repair. The loading with the C-141 area shows that Position 3 gives a higher stress than Position 1. This is attributed to the wide load distribution of the C-141 main gear which, unlike the F-4 main gear, is not influenced by the surrounding portland cement concrete. Although Position 1 gives flexural stresses that are not significantly lower than those obtained in Position 3, it was decided that the design for Position 3 will satisfy the condition of Position 1.

In summary, only Position 2 (representing edge condition) and Position 1 (representing interior condition) were considered significant for the F-4. Only Position 2 (representing edge condition) and Position 3 (representing interior condition) were considered significant for the C-141.

For the C-141 aircraft, which has a dual tandem gear configuration, the two positions shown in Figure 69 were analyzed and the results indicated that loading the gear tires on the center of the repair gives the most critical stresses, and this position was used for further analysis.

Another problem with the C-141 dual tandem gear was to locate the maximum flexural stresses. The results showed that they occur directly under the tire.

The results presented in Figures 70 and 71 indicate that varying the runway support has no influence on the flexural stresses. The runway support was then fixed at 300 pci, which is slightly above the average (250 pci) existing at European bases. Although the 300 pci does no influence the results, it permits the user to consider repair support K_{pc}'s up to 300 pci, because of the primary assumption, i.e., $K_{repair} \leq K_{runway}$.

For a 17 x 17 foot repair, varying the runway thickness does not influence the flexural stresses significantly (Figure 72). The runway thickness was then fixed at 12 inches. The value of 12 inches was selected because it represents a good average encountered in the field and it does not influence the results. For a 5 x 5 foot repair, the runway thickness has definite influence. The values of 12 inches and 16 inches were used as representing thin and thick pavements, respectively, while the value eight inches was rejected because very high stresses were obtained by loading a 8-inch pcc slab, indicating that the runway is underdesigned.

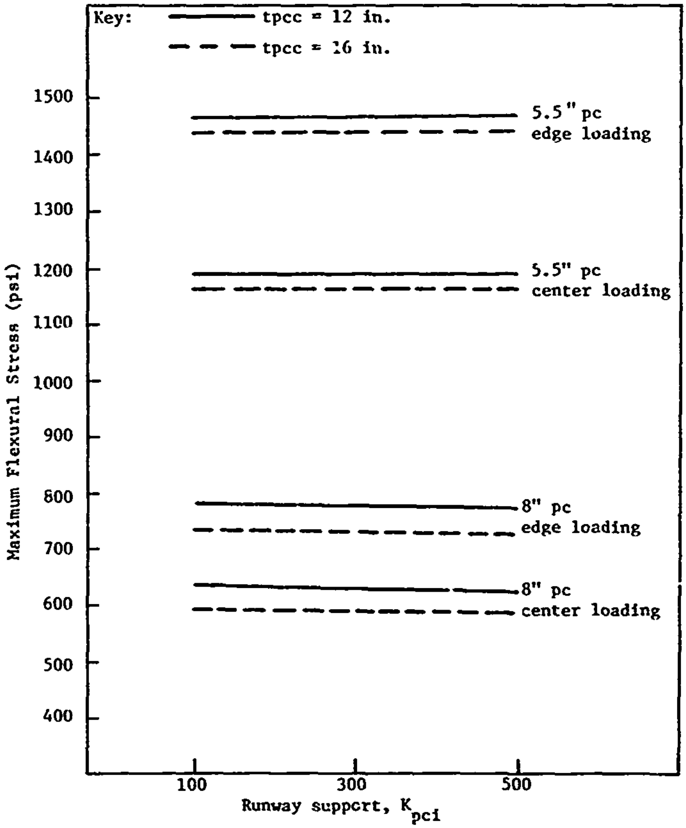


Fig. 70. Stress Versus Runway Support for F-4 Loading 5 x 4.5-Foot Repair and K_{pc} = 50 pci

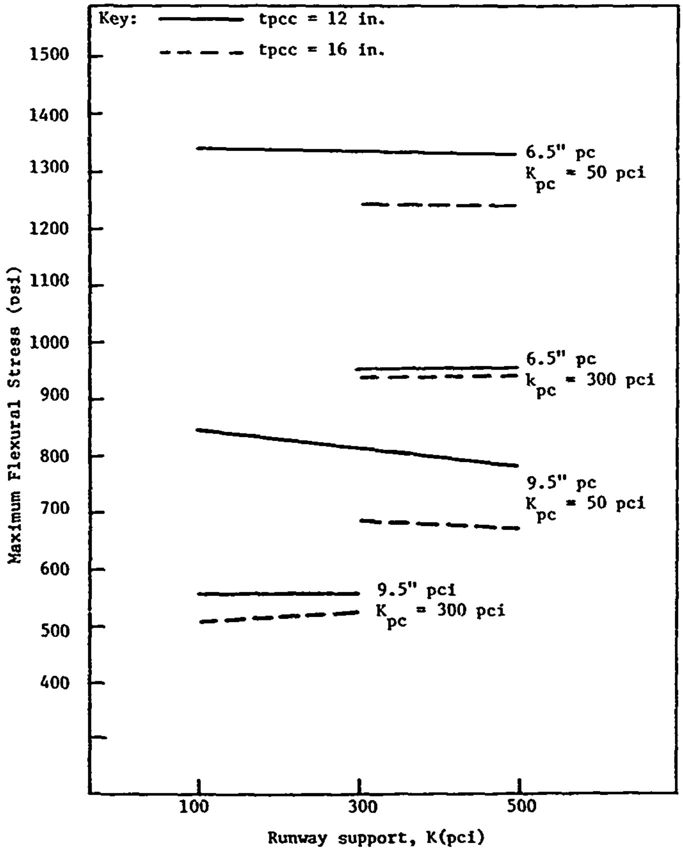


Fig. 71. Maximum Flexural Stress Versus Runway Support for C-141 Loading and 5 x 4.5-Foot Repair

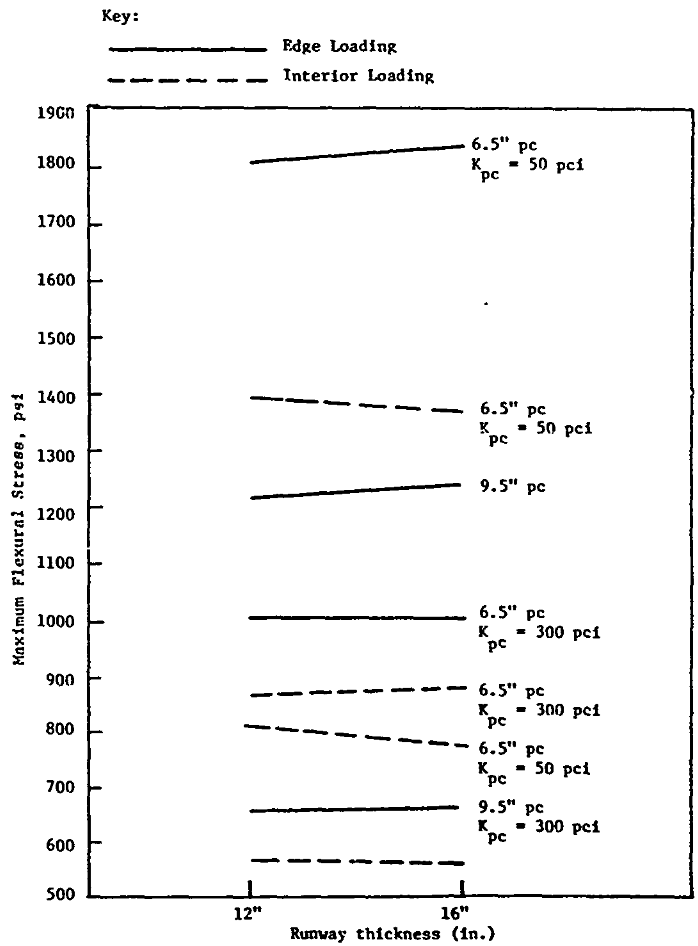


Fig. 72. Maximum Flexural Stress Versus Runway Thickness for 17 x 17-Foot Repair and C-141 Aircraft

The repair support has an influence on the results, and the values 50 pci and 300 pci were selected as representing the extremes (poor and strong support).

The stresses resulting from all conditions where K_{pc} = 300 pci and Position 2 (edge) was loaded are plotted and the boundaries of stresses for the F-4 and the C-141 are shown in Figure 73. Because the range of stress was small, only the upper boundary of each of the F-4 and the C-141 was used as representing the edge loading, with K_{pc} = 300 pci for all conditions, thus reducing the scope of analysis.

5.3 Design Charts

After the Sensitivity Study reported in subsection 5.2, design charts were prepared containing only the significant variables as defined by the Sensitivity Study. Figures 74 through 77 are design charts that present the maximum flexural stress in terms of the polymer concrete repair depth for a range in conditions. On the chart, qualitative variables are used, whereas the previous information has been developed in terms of quantitative factors. The qualitative factors are:

- Small repair size equals 25-299 square feet.
- Large repair size equals 300-999 square feet.
- Major replacement equals 1000 or greater square feet.
- Strong repair support equals 300 pci plus.
- Poor repair support equals 50 pci.
- The thick existing runway equals 16 inches.
- The thin existing runway equals 12 inches.

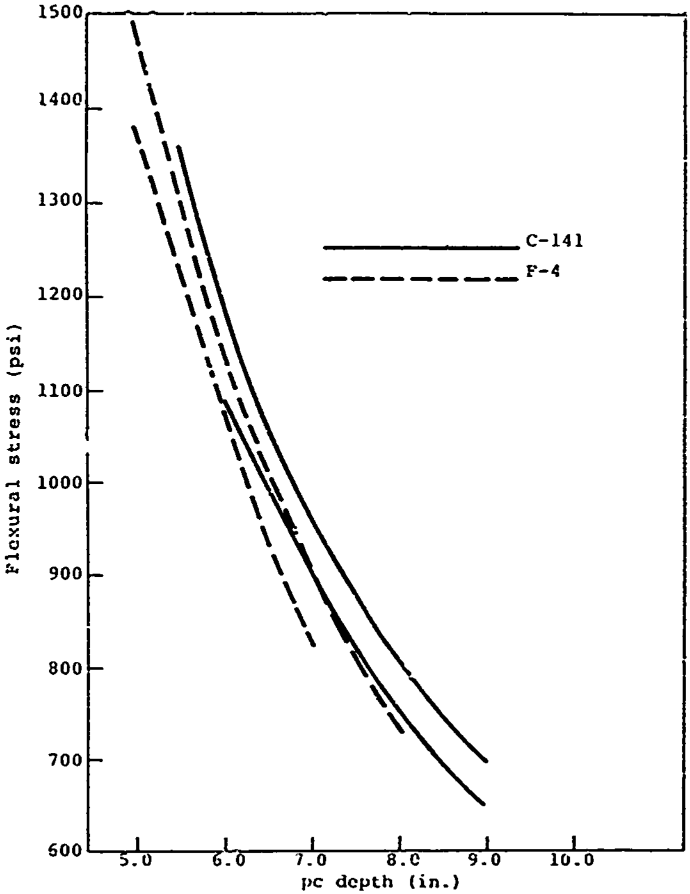


Fig. 73. Flexural Stress Versus PC Depth for Edge Loading and K_{pc} = 300 pci

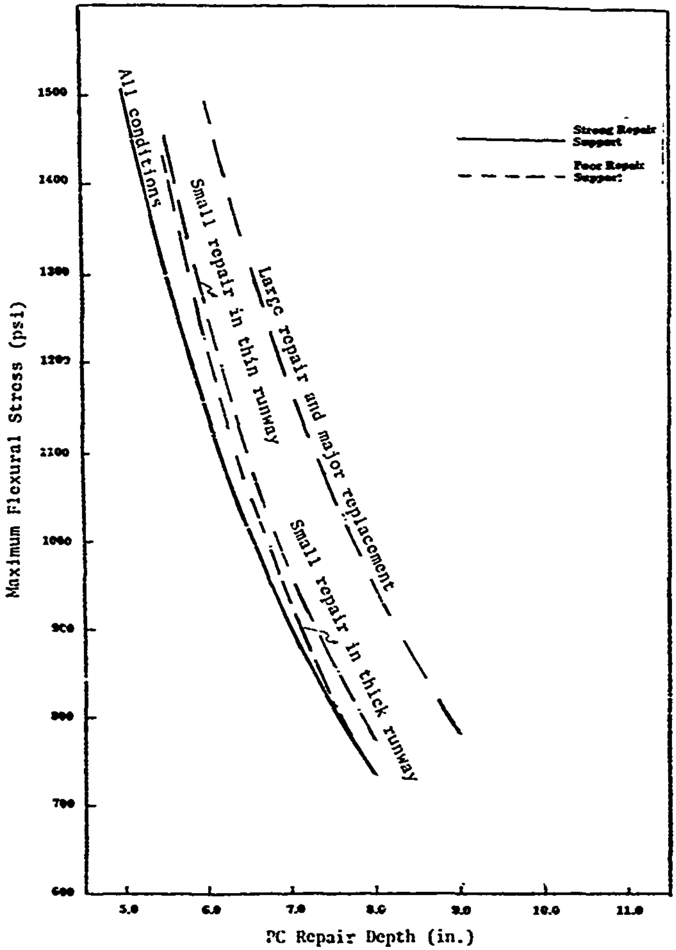


Fig. 74. Polymer-Concrete Thickness Design Chart for F-4 Aircraft and Edge Loading

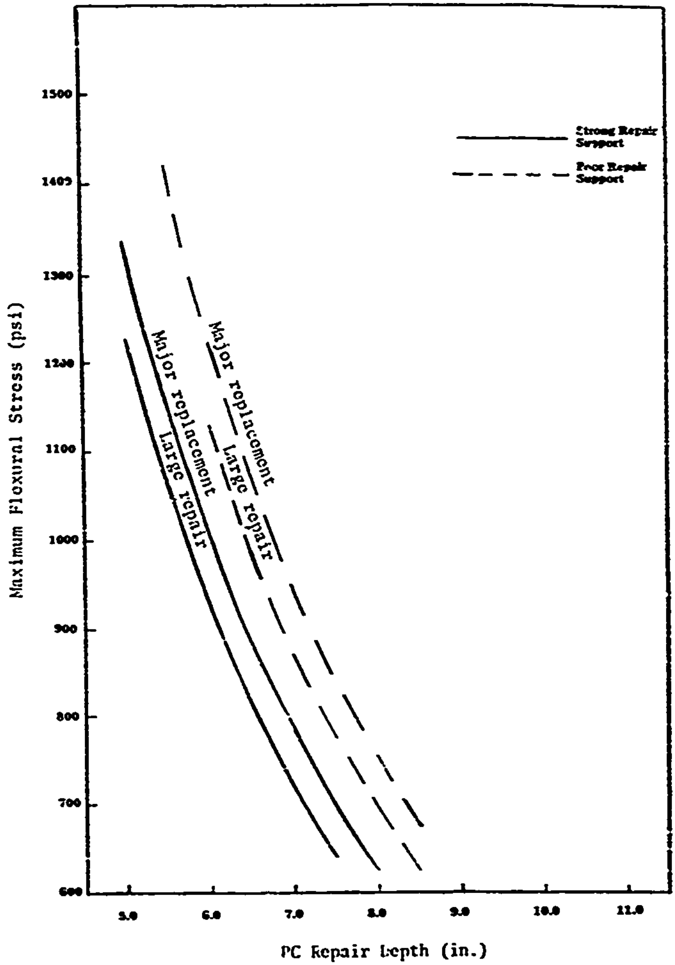


Fig. 75. Polymer-Concrete Thickness Design Chart for F-4 Aircraft and Interior Loading

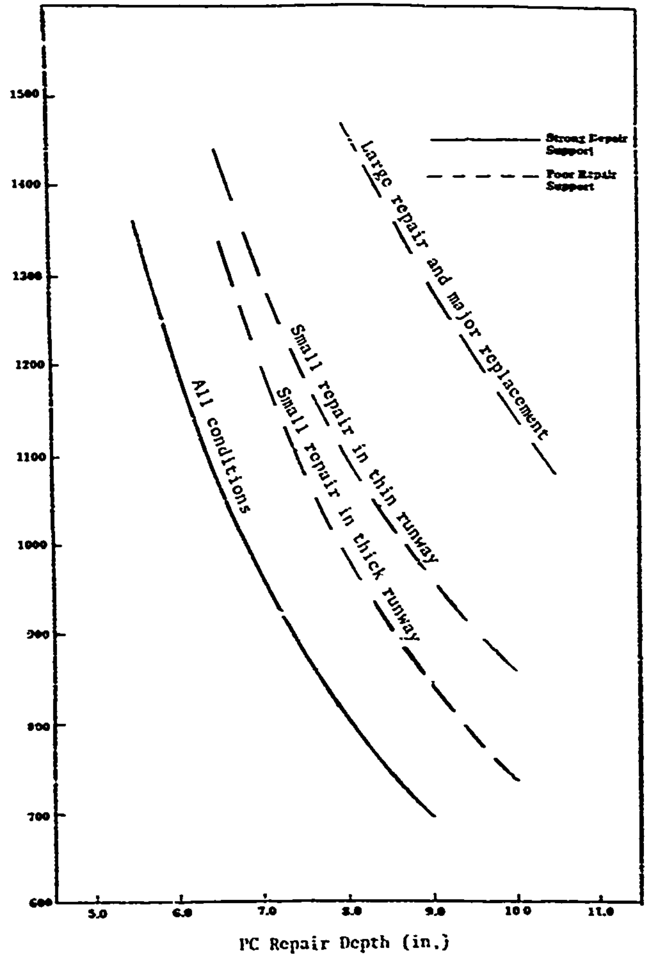


Fig. 76. Polymer-Concrete Thickness Design Chart for C-141 Aircraft and Edge Loading

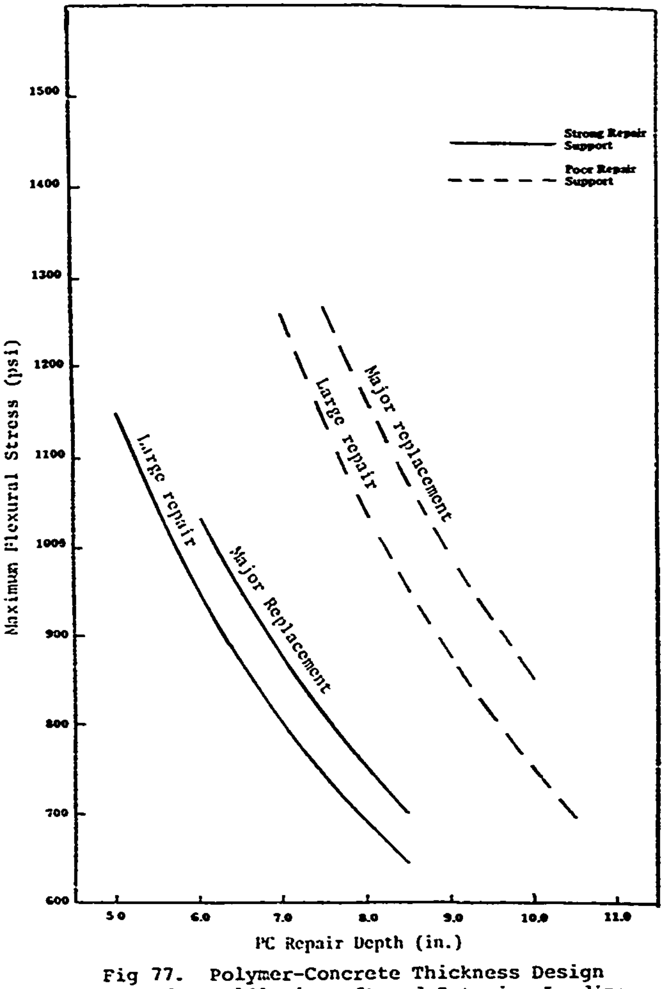


Fig 77. Polymer-Concrete Thickness Design Chart for C-141 Aircraft and Interior Loading

Figures 74 and 75 present the maximum flexural stress in polymer concrete versus polymer concrete repaired area thickness for the F-4 aircraft for edge and interior loading, respectively. Figures 76 and 77 present the same information for the C-141 aircraft for the edge and interior loading, respectively.

For simple use of the charts, the user should consider only the edge loading for the small repairs, whereas for larger repairs and major replacement the user should consider either edge or interior loading conditions. In using the chart, the designer may interpolate the value of the repair support. For the repair size, the designer determines a size and then finds the range that encompasses the appropriate figure. For example, if the repair area is 225 square feet, the user would select the larger repair size for determining the polymer concrete thickness. If the repair area encompasses the edge, the edge condition should be selected. If the repair area is surrounded by the existing pavement, an interior loading condition is used.

The allowable stress level to be used in the equation must be derived as a function of the number of repetitions. Therefore, the fatigue concept is applicable here. The following equation represents a typical fatigue equation that is used for portland cement concrete:

$$N = A\left(\frac{f}{\sigma}\right)^{B} \qquad (1)$$

where σ = the stress in the polymer due to the appropriate aircraft loading and other condition.

f = the flexural strength of the polymer concrete.

N = the allowable number of repetitions for the strength and stress condition.

A & B = coefficient for testing of the specific materials.

The above equation has been used for the design of portland cement concrete and asphalt concrete for a substantial period of time and is felt to be applicable here. The coefficient A and B have not yet been developed for polymer concrete but will be developed in the very near future. Since all static-type tests on the polymer concrete have indicated that this is vastly superior to the normal portland cement concrete, it is felt that the use of coefficients developed for portland cement concrete will be conservative. Therefore Equation (1) is defined as follows for polymer concrete:

$$N = 23{,}440 \left(\frac{f}{\sigma}\right)^{3.21} \qquad (2)$$

where all variables are as defined previously.

5.4 Design Procedure

The following is a sequential procedure that may be used by the user at a given facility to determine the thickness of polymer concrete repair:

1. Action should be taken to determine the thickness of the existing concrete pavement and the relative applications of each type of aircraft of the two design aircraft, i.e., C-141 and F-4, and a judgment should be made as to the compaction condition to be used in the field or repair area, i.e., poor or good. In addition, a decision should be made as to the length of time that design applications are to be applied.

2. The user uses the repair area and makes qualitative decisions as to small, large, or major repair replacement, and a decision is made as to whether the repair is an edge, i.e., whether the repair is surrounded by existing pavement.

3. The allowable stress for the aircraft is computed for each aircraft type using the following equation:

$$\sigma = f \left(\frac{23440}{N} \right)^{0.31} \quad (3)$$

4. The user then determines the polymer concrete repair by entering the appropriate figure from Figures 74 through 77 to represent the aircraft type and loading condition. The allowable stress from step 3 is entered at the vertical axis projected horizontally to the appropriate repair area and support condition. At that intersection, the line is projected vertically and the thickness is read on the horizontal scale.

SECTION VI

SUMMARY AND CONCLUSIONS

6.0 Summary

The use of methyl methacrylate polymer concrete has been investigated for bomb damaged runway repair. Criteria included: (1) set times of one hour or less at temperatures in the range of $-25^{\circ}F$ to $125^{\circ}F$; (2) set times of one hour less when in contact with asphalt; and (3) develop adequate strength when used with wet aggregate. Mechanical properties (flexural strength, modulus of elasticity and fatigue strength) have been found. User-formulated and commercially-available prepackaged materials were investigated. The effect of aggregate size and gradation was studied.

Preliminary repair procedures were developed for four types of bomb damage: (1) surface spalls; (2) small craters; (3) large craters; and (4) camouflet. Techniques for placing the polymer concrete were studied.

Laboratory behavior of polymer concrete was begun to determine fatigue behavior of beams and repaired slabs, compressive strength, flexural strength, and modulus of elasticity. Several repair configurations on 3 x 6 foot slabs are being studied, and loads are applied to simulate the F-4 and C-141 aircraft until failure occurs or for a maximum of 100,000 load cycles.

Analytical behavior of repairs has been made for a wide range of repair sizes, edge conditions, thicknesses, and support conditions. Both F-4 and C-141 aircraft loadings were considered.

6.1 Conclusions

Based upon the studies completed in Phase I, the following conclusions can be made.

6.1.1 Materials Characterization.

1. Monomer systems consisting of MMA/TMPTMA or MMA/TTEGDA behave similarly; MMA/TTEGDA systems develop slightly more ductility and can cure at lower temperatures. MMA/TTEGDA was polymerized in one hour or less at temperatures as low as $-25^{\circ}F$. The effect of monomer temperature was found to exert a very strong influence on the setting time.

2. The effects of casting temperature and testing temperature were not very significant. The strengths were slightly higher and the ductility was less with decreasing temperature.

3. The loading rates used in this study, 47.16 psi/sec and 22.58 psi/sec, produced only slight differences in the strength and behavior.

4. The bond of PC to PCC tested at $136^{\circ}F$ was 600 psi or higher except for PC cast at $100^{\circ}F$, for which the strength was lower.

5. The flexural bond of PC to PC was found to be excess of 900 psi.

6. The flexural strengths of PC made with dry aggregate were generally found to be about 2000 psi or higher.

7. Prepackaged PC systems produced PC with similar properties as the user-formulated system.

8. The use of different aggregate sizes and gradation did not appreciably alter the mechanical properties.

9. Compressive and tensile strength of wet aggregate was reduced very significantly with increasing moisture content for both limestone and silicious aggregate. Of the many techniques studied to increase the strength; the use of silane coated-aggregate and the use of steel fibers added to the PC mix were found to be . .. most effective in maintaining adequate tensile strengths with increasing moisture content.

10. Asphalt was found to inhibit the polymerization of MMA, but acceptable shear strength and cure times were achieved.

6.1.2 Preliminary Repair Procedures.

1. Two PC systems are recommended for further field testing: (1) user-formulated MMA system using an in-line mixing system for applying the monomer over the preplaced aggregate and (2) prepackaged commercially-available PC systems extended with coarse aggregate.

2. Spall repairs can be made using debris if it is free of asphalt and has a maximum aggregate size of 3/4-inch or less; if the aggregate size is larger than 3/4-inch, fine aggregate

must be added. User-formulated monomer system is recommended in conjunction with the in-line mixing system.

3. Small crater and camouflet repairs can be made using the cap method for small areas and precast units for larger areas. In either method the crater is filled within 10 to 14 inches of the surface with debris and then compacted with a vibratory roller. A levelling course of select material is placed.

a. Cap method. The levelling course is primed and and sealed using the in-line mixing system prior to using the preplaced aggregate method or the premixed PC to make the repair.

b. Precast slab method. Precast units should be sized to be modular with the existing pavement slabs. The slabs should be positioned to provide 4- to 6-inch joints. The slabs may be either placed flush with PC used to fill the joints, or slabs may be recessed with PC used in the joints and an overlay. Both user-formulated and prepackaged PC should be considered for these repairs.

4. Larger crater repairs can be made using the precast slab method using either the user-formulated or prepackaged PC systems.

6.1.3 Experimental Behavior.

1. Laboratory studies underway indicate that polymer concrete repairs have high resistance to cyclic loadings even when cracking is present in the repair.

2. Initial tests on PC beams indicate long fatigue life, although some creep occurs, of up to 2,000,000 load cycles.

6.1.4 Analytical Behavior.

1. The nose gear has no influence on the stresses and may be neglected in the analysis.

2. The critical positions for the location of the gear were on a horizontal centerline at each edge and at the center of the repair. For the F-4, the critical locations were the center and the outside edge; for the C-141, the inside edge abutting the PCC pavement was critical.

3. The value of the runway (PCC) support has no significant effect on flexural stresses.

4. For larger repairs, the runway thickness has little influence on the flexural stresses; for small repairs, the effect is significant.

5. Repair support values must be considered; limiting values of 300 pci and 50 pci were used.

6. Design charts are presented to simplify the design of the PC repairs.

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APPENDIX A

AGGREGATE GRADATION AND PROPERTIES AND CONCRETE MIX DESIGN

Appendix A contains data pertaining to the aggregate gradation and physical properties and the mix design for portland cement concrete used in the research. The tables included are as follows:

Table A-1 Sieve Analysis of Blasting Sand

Table A-2 Mix Design Proportions of the Portland Cement Concrete Used in the Experimental Program

Table A-3 Properties of Colorado River Sand

Table A-4 Physical Properties of Sand and Pea Gravel

Table A-5 Aggregate Gradation

Table A-6 Physical Properties of Aggregate

Table A-1. SIEVE ANALYSIS OF BLASTING SAND

U.S. Sieve Size	Percent Retained
#8	0.61
#16	14.62
#30	14.00
#50	54.50
#100	15.23
Pan	1.04

Table A-2. MIX DESIGN PROPORTIONS OF THE PORTLAND CEMENT CONCRETE USED IN THE EXPERIMENTAL PROGRAM

Component	Amount (lb)
Cement	13.4
Water	6.6
Fine Aggregate	22.6
Coarse Aggregate	18.0

Table A-3. PROPERTIES OF COLORADO RIVER SAND

Sieve Analysis of Colorado River Sand

U.S. Sieve Size	Percent Retained
#4	0.51
#8	10.56
#16	19.64
#30	37.69
#50	21.73
#100	8.14
pan	1.73

Bulk specific gravity = 2.55
Bulk specific gravity, saturated surface-dry condition = 2.60

Table A-4. PHYSICAL PROPERTIES OF SAND AND PEA GRAVEL

Grade 4

	3/8" max. crushed lime pea gravel		All-purpose sand	
Bulk sp. gr.	2.39		2.61	
Absorption	3.10		1.02	
Gradation	sieve size	percent retained	sieve size	percent retained
	#3(1/4")	4.5	#8	9
	#4(1/8")	6.0	#16	23
	#8(.0937")	98.5	#30	48
	#10(.0787")	99.5	#50	82
			#100	98
	Pan	100%	Pan	100%

Table A-5. AGGREGATE GRADATION

50% All-Purpose Sand and 50% Grade 4[a]	Percent Retained by Weight
1/2	0.0
3/8	10.0
#4	35.5
#10	5.5
#20	7.5
#30	11.5
#40	13.5
#50	2.0
#60	5.0
#80	0.5
#100	0.5
Pan	0.5

[a]Texas Department of HSPT Specification

Table A-6. PHYSICAL PROPERTIES OF AGGREGATE

	3/8" crushed lime pea gravel		3/8" max. silicious round pea gravel		All-purpose sand	
	uncoated	coated	uncoated	coated		
Bulk sp. gr.	2.39	2.37	2.57	2.50	2.61	
Absorption, %	3.10	0.95	1.08	0.76	1.02	
Monomer Loading[a], %	-	2.99	-	0.77	-	
Gradation	sieve size	percent retained	sieve size	percent retained	sieve size	percent retained
	#3	4.5	#3	61.8	#8	9
	#4	6.0	#4	91.9	#16	23
	#8	98.5	#8	98.9	#30	48
	#10	99.5	#10	99.0	#50	82
					#100	98
	Pan	100%	Pan	100%	Pan	100%

[a] $\frac{\text{Coated weight} - \text{Uncoated weight}}{\text{Uncoated weight}} \times 100$

INITIAL DISTRIBUTION

DTIC-DDA-2	12
HQ AFSC/DLWM	1
HQ AFSC/SDNE	1
HQ AFSC/DEE	1
HQ AFSC/DEM	1
HQ USAFE/DEMY	1
HQ USAFE/DEM	1
HQ USAFE/DEX	1
HQ USAFE/EUROPS (DEXD)	1
AFATL/DLJK	1
AFATL/DLODL	1
AD/IN	1
USAFETAWC/RX	1
USAFTAWC/THL	1
USAFTAWC/THLA	1
EOARD/LNS	1
SHAPE Tech Center	1
HQ PACAF/DEE	1
HQ PACAF/DEMM	1
HQ PACAF/DEM	1
HQ PACAF/DEPR	1
HQ TAC/DEE	1
HQ TAC/DRP	1
AUL/LSE 71-249	1
COMMCBLANT	1
AFISC/IGQB	1
HQ SAC/DE/DEE/DEM	1
US Navy Civil Engrg Lab	1
HQ ATC/DED	1
HQ ATC/DEE	1
HQ MAC/DEM	1
HQ AFESC/DEMP	1
HQ AFESC/DEO	1
HQ AFESC/TST	1
HQ AFESC/RDCR	1
BDM Corp	2
USAE WESGF	1
HQ USAF/LEEX	1
HQ USAF/LEYW	1
HQ USAF/RDPX	1
AFWAL/MMXE	1
AFWAL/FIEM	1
AFWAL/FIBE	1
HQ AFLC/DEMB	1
HQ AFLC/DEE	1
AFIT/DET	1
AFIT/LDE	1
ASD/TAAMF	1
819 CESHR/CC	1
200 CESHR/CC	1
201 CESHR/CC	1
Det 1, 307 CESHR/CC	1
[illegible]07 CESHR/CC	1
[illegible]4 CESHR/CC	1
Det 1, 554 CESHR/CC	1
820 CESHR/CC	1
823 CESHR/CC	1
HQ AAFCE	1
TAC ZEIST	1
559 CE CFE HQ	1
HQ 3 in C, Moduk (Army)	1
Luftwaffenpionierlehr Kom.	1
LuftflottenKommando A3V	1
Etat-Major	1
Etat-Major Force Aerienne	1
Fixed Wg Eng Tech Sec, A&AEE	1
Defense Equip. Staff Brit	1
Procurement Exec, Min of Def	1

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